Colegio de Postgraduados

Agriculture 4.0: Is Mexico Ready?

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ABSTRACT

Objective: To analyze the possibilities and actions required to foster the introduction of technologies consistent with the term "agriculture 4.0" in Mexico.

Design/Methodology/Approach: To identify providers of technology in Mexico. To present the cost-benefit equation regarding the adoption of said technology as applied to the cultivation of maize in different regions. To design and construct an adoption propensity index that will serve as a basis to propose focused and adequate actions to remove technology access barriers.

Results: Mexico has a young and wide offer of technology, both tangible and intangible, where digital platforms of agricultural management, mobile apps, and remote monitoring predominate. The cost-benefit relationship offers a large margin to adopt new technologies. However, there are adoption barriers (related to education or infrastructure, for instance) that represent a challenge to different regions of the country: the northern, northeastern, and western states of Mexico are more likely to adopt new technologies.

Study limitations/Implications: Further experimental and field analyses are required to delve deeper into potential additional barriers (culture-related, for example).

Findings/Conclusions: The cost-benefit analysis offers a large margin for adoption. However, the propensity to adopt is associated to restricting factors such as the producers' educational level, the production unit's size and level of mechanization, the access to and use of Information and Communication Technologies, and the telecoms infrastructure, whose geographic disparity is significant. The public sector's intervention is desirable to reduce the gap between the supply and demand of technologies, as well as the access barriers to the latter.

Key words: Precision agriculture, Digital gap, Technology adoption, Intangible technologies.

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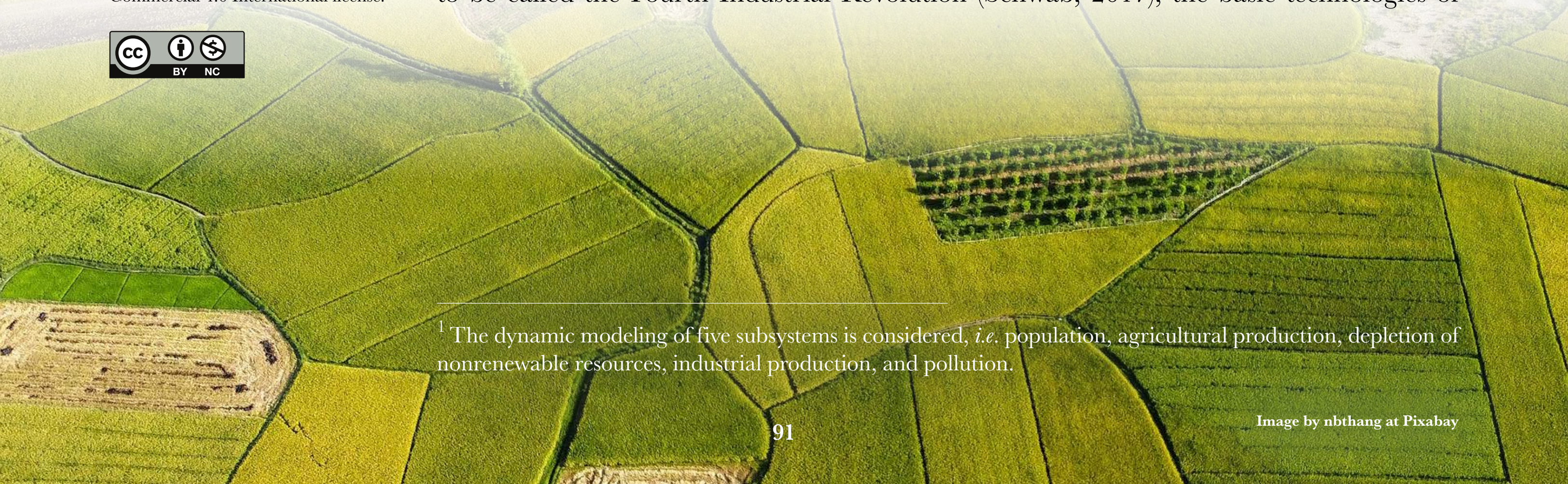
INTRODUCTION

In 1968, the Club of Rome (Meadows *et al.*, 1972) challenged the limits that our natural environment imposes on the growth of human activity.[1] The results sounded the alarm due to the bleak conclusions drawn by the participants when illustrating the excess processes that can be reached, and to the scenario of collapse they laid out for humanity in the 21st century were the collective course of action not rectified. At the same time, the current technological advances combine diverse spheres of knowledge and have come to be called the Fourth Industrial Revolution (Schwab, 2017), the basic technologies of

[1] The dynamic modeling of five subsystems is considered, *i.e.* population, agricultural production, depletion of nonrenewable resources, industrial production, and pollution.



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the current revolution are, among others: the Internet of Things (IoT), cloud computing, big data management, 5G, artificial intelligence, 3D printing, robotics, and virtual and augmented reality.

At the center of this crossroads lies an essential element of the limits to growth: the supply of natural resources to provide food for the population. The consumption, growth, and depletion of said resources is largely related to the available amount of arable land. According to FAO, the amount of arable land per capita in the world in 1961 was 0.45 ha. This figure dropped to 0.21 available ha in 2016 and maintains an estimated annual reduction rate of 0.08 ha per capita. Based on FAO data, yield improvements will be the main source of production increases (78% of improvements between 1961-1999 and 70% towards 2030).

Unlike the previous periods, the subsequent expansion stage of agricultural productivity will face unprecedented challenges such as: i) a historically low availability of agricultural lands; ii) a changing climate that manifests in greater episodes of drought, floods, and extreme heat waves; and iii) restrictions in the use of energy and fertilizers due to the greater conscience regarding the impact of agricultural activities on the environment, among other limiting factors.

Two periods of significant advances are identified in the group of technologies related to the fourth industrial revolution: 1990 to 2014, a period associated to precision agriculture, and 2015 to date, linked to smart farming and agriculture 4.0. The new technologies will bring a greater availability of foods worldwide; however, foreseeing the impact of said technologies in a country like Mexico is still difficult due to the great inequalities that characterize its primary sector.

To help understand the technological advances, this article sets out to describe how the new technologies are made up, what their supply and demand potential is in the Mexican context, as well as to identify the potential barriers that are keeping us from turning these technologies into an opportunity to reduce —instead of widening— the development gap in rural Mexico.

MATERIALS AND METHODS

The adoption of new technologies for agricultural development is usually heterogenous among and within countries. A publication search in the "ScienceDirect" platform was done using the key terms "Precision Agriculture", "Smart Farming", and "Digital Agriculture" / "Agriculture 4.0", in order to examine the performance reports, obstacles, and results of applying this technology. The presence of the terms in article key words, abstracts, or titles was emphasized.

To identify the degree of adoption and the provider profile in Mexico, we turned to the new technologies adoption database recently prepared by Fideicomisos Instituidos en Relación con la Agricultura (FIRA).[2] The nature of technological innovation was

[2] FIRA tends to Mexico's rural, agricultural, forest, and fishing sectors by granting loans, guarantees, and technical assistance through a vast network of associate businesses and around 100 offices throughout the country. https://www.fira.gob.mx

emphasized based on a distinction commonly made in agricultural economics (Sunding & Zilberman, 2001) regarding the type of technologies for agricultural production, which in turn can be divided into tangible or embodied[3] and intangible or disembodied[4] technologies. The viability of the adoption of new technologies in the country was subsequently assessed based on the assumption that the total income after adopting said technologies should be higher than the total income before such adoption. The variable income per hectare I_{ha} was thus defined and expressed as a function of the yield per hectare Y_{ha} and the cost per hectare C_{ha}, according to the following equation:

$$I_{ha} = Y_{ha} - C_{ha} \tag{1}$$

The necessary condition to adopt the technology is:

$$I_{ha}^{t} \geq I_{ha}^{t0} \tag{2}$$

Where superscript t describes the technology that allows us to define income I_{ha}^{t}. We used $\alpha(t)$ to designate a change factor of production per hectare due to the adoption of technology t, and $\beta(t)$ to designate a change factor of cost per hectare due to the adoption of technology t. Both $\alpha(t0)=0$ and $\beta(t0)=0$, where $t0$ is the original technology. The variable is defined as follows:

$$Y_{ha}^{t} = N_{ha}^{t} * P_{crop}$$

and

$$C_{ha} = Cind_{ha}^{to} + Cdep_{ha}^{t}$$

where

$$N_{ha}^{t} = (1+\alpha(t)) * N_{ha}^{t0} \text{ and } Cdep_{ha}^{t} = Cdep_{ha}^{t0}(1+\beta(t))$$

Where N_{ha}^{t0} is the number of tons per hectare yielded by the crop when using the initial technology $t0$; P_{crop} is the price of the crop; $Cind_{ha}^{t0}$ is the cost per hectare of producing the crop, where the cost is independent from the used technology, while $Cdep_{ha}^{t}$ is the corresponding cost, where the cost is dependent on technology t. Substituting equation (1) in equation (2), the following condition ensues:

[3] These technologies are incorporated into physical devices such as agricultural machinery, sensors for animals or plants, drones and robots, among others.

[4] These technologies comprise, for instance, remote consultancy platforms, software to manage and monitor crops, and digital platforms boosted by data mining.

$$\left(1+\alpha(t)\right)*N_{ha}^{t0}*P_{crop}-\left(Cind_{ha}^{t0}+Cdep_{ha}^{t0}\left(1+\beta(t)\right)\right)\geq N_{ha}^{t0}*P_{crop}$$
$$-\left(Cind_{ha}^{t0}+Cdep_{ha}^{t0}\right) \quad (3)$$
$$\alpha(t)\geq\frac{Cdep_{ha}^{t0}}{N_{ha}^{t0}*P_{crop}}\beta(t)$$

Inequality (3) represents the change factor in production necessary for the producer's income to be greater with technology t than with respect to the existing technology of each crop t0. Finally, to analyze the natural access barriers to new technologies we created a development index (UNDP, 2022) considering four development variables that restrict the adoption of agriculture 4.0 technologies: production unit size, 3G and 4G coverage, educational lag and level of Information and Communication Technologies (ICT) use, and degree of agricultural labor mechanization. All of this was based on information from four surveys.[5]

RESULTS AND DISCUSSION

The term agriculture 4.0 was first used as one of many extensions of the "fourth industrial revolution" (Schwab, 2017). Figure 1 shows two development stages of the new technologies as applied to agriculture. The first one (1998-2014) refers to precision agriculture, which according to the National Research Council (1998) is an "IT management strategy to obtain data from multiple sources to make them relevant in decisions related to crop production". Precision agriculture considers three basic components: data capture at an appropriate frequency and scale, their interpretation and analysis, and the implementation of a managerial response in the appropriate time and size. The information sources generally come from tools developed for other spheres of scientific activity, such as satellites, multispectral cameras, or sensors. The increase in the number of bibliographic references largely linked to digital and smart farming from the period 2014-2017 is noteworthy. From this period onwards, articles refer to big data technologies (Wolfert *et al.*, 2017), cloud computing (Pivoto *et al.*, 2018), digital innovation (Ayre *et al.*, 2019), the Internet of Things (Doshi *et al.*, 2019), and artificial intelligence (Spanaki *et al.*, 2021), none of which were available during the preceding period. All of these technologies led to a natural evolution of precision agriculture.

International service providers

Birner *et al.* (2021) identified four types of agricultural technology providers.

[5] Censo Agrícola, Ganadero y Forestal (2007) for production units and land areas; Instituto Federal de Telecomunicaciones and Secretaría de Agricultura y Desarrollo Rural (IFT-SADER, 2020) for 3G and 4G coverage; Encuesta Nacional Agropecuaria (ENA, 2019) for variables related to the use of tractors, educational level, and the use of ICT in production units.

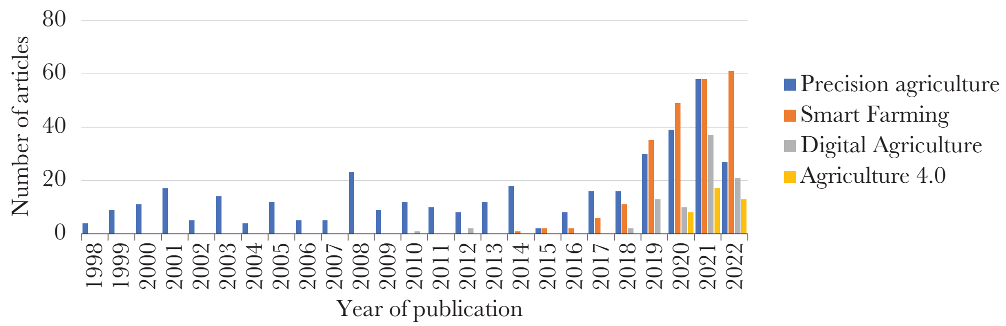


Figure 1. Bibliographical references relevant to agricultural technology innovation

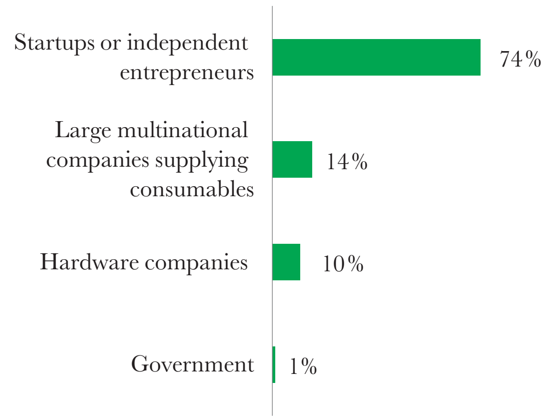
Table 1. Types of technology providers.

Type of provider	Value offer	Examples
Large multinational companies supplying consumables	They provide services alongside their products and have a great capacity to invest in research and development (R&D), and to distribute their services through their commercial networks.	Bayer, Syngenta, Monsanto, DuPont, Yara.
Large software and hardware multinational companies	Large software companies with the capacity to gather and process very vast databases.	IBM, Microsoft, SAP, TENCENT, Alibaba, Google.
Hardware companies (not necessarily agricultural)	They have economies of scales and give added value to their main lines of business (*e.g.* machinery).	Bosch, John Deere, Airbus, XAG, Massey Ferguson, Fendt, Kubota.
Startups or independent entrepreneurs (not necessarily specialized in the agricultural sector)	Agility and innovation, as well as specialization in added value services for producers.	DigiFarm, Hello Tractor, Xarvio app, RML AgTech, Cropin.

Based on the survey results, we identified 86 technology providers in Mexico, most of them (74%) startups or independent entrepreneurs who offer both tangible and intengible technology. In contrast, we could not find any software provider with a large multinational company profile. Meanwhile, the large hardware companies are scarce in the country; they represent 10% of the total. In the latter category, we found companies such as John Deere, Massey Ferguson, and XAG. In short, these providers offer technologies related to agriculture 4.0 in Mexico: 49 of them offer technologies classified as tangible (57%) and 37, as intangible (43%) (see Figures 2 and 3).

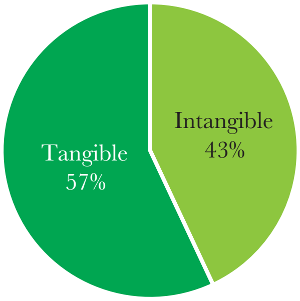
During the last 14 years, the adoption of these technologies has increased, with a tendency to adopt more intangible technologies than tangible ones. Digital platforms of agricultural management were more present in 2018, mobile apps in 2019, and drones and agrobots in 2020.

In the end, we found an adoption process in place for a wide range of technologies in different production chains in Mexico, comprising basic grains, vegetables, and perennial crops. Maize stands out as the main crop to have adopted the different types of technology, both tangible and intangible, which is consistent with the socioeconomic importance this crop has in Mexico.



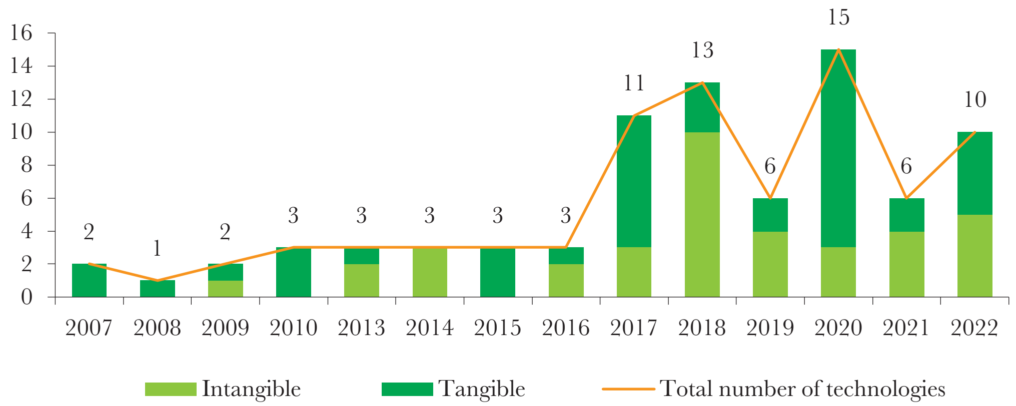
Source: Own elaboration based on information gathered by FIRA.

Figure 2. Technology providers in Mexico.



Source: Own elaboration.

Figure 3. Percentage of tangible and intangible technologies in Mexico



Source: Own elaboration based on information gathered by FIRA.

Figure 4. Historical series of technology adoption in Mexico, 2007-2022

Table 2. Characterization of technology types by agricultural chain and year of adoption.

Type of technology	Technology	Main agricultural chains where it is applied	Year of first adoption
Tangible	Drones	maize, wheat, cane, barley, vine, agave, cotton, tomato, citrics	2002
	Agrobots	Various crops	2016
	High-end tractors	maize, rice, banana, lemon, watermelon, melon, milk	2000
	Agricultural devices	maize, sorghum, bean, fava bean, sunflower, among other seeds	2005
	Monitoring system	maize, green chili, garlic, tomato, and milk	1995
Intangible	Apps	maize, barley, honey, vegetables, fruits, dairy products, meat, seafood, and pine tree	2013
	Digital platforms of agricultural management	maize, wheat, palm oil, apple, honey, lemon, vegetables, and coffee	2002
	Research & Development	Various crops	1982

Source: Own elaboration based on the information gathered by FIRA.

Potential demand of services in Mexico

The adoption of new technologies must meet the condition of generating a higher income for the producer, once the acquisition costs have been considered. This condition can be met under different parameters according to a series of production-related conditions, such as crop type, production region, currently available technology, product prices, as well as the component impacted by the new technology. Thus, considering production costs and yields databases[6] by geographical zone, we analyze different scenarios that will allow us to assess the productivity increase thresholds that are necessary to generate demand for new technologies.

The starting point to analyze this sensibility was the condition presented in equations (2) and (3). We chose three states with different advancement levels in maize productivity: Sinaloa (high productivity), Morelos (intermediate productivity), and Tlaxcala (low productivity). We assumed the adoption of a technology impacting fertilization costs.

Table 3. Analysis of the adoption of new technologies.

State	N_{ha}^{t0}	P_{maize} (\$)	$Cdep_{ha}^{t0}$ (\$)	$\frac{Cdep_{ha}^{t0}}{N_{ha}^{t0} * P_{crop}}$
Sinaloa	12	6,075	17,034	0.234
Morelos	7.5	6,500	9,722	0.199
Tlaxcala	4.85	6,300	3,974	0.130

[6] Agrocostos FIRA www.fira.gob.m/agrocostos.

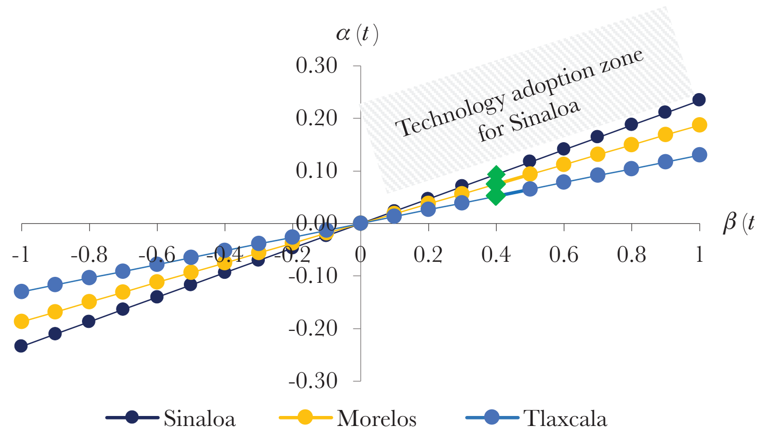


Figure 5. Change factor of maize productivity in Sinaloa, Morelos, and Tlaxcala

The slopes of the straight lines calculated define the new technologies adoption zone depending on the effect on production cost β_t. This zone is broad and lies above the straight lines according to:

$$\text{Sinaloa } \alpha(t) \geq 0.234 * \beta(t), \text{ Morelos } \alpha(t) \geq 0.199 * \beta(t), \text{ Tlaxcala } \alpha(t) \geq 0.130 * \beta(t)$$

In turn, the line delimiting the adoption threshold depends on the region's productivity N_{ha}^{t0}, the price of the product P_{maize}, and the cost associated to the adopted technology $Cdep_{ha}^{t0}$. In this regard, Figures 6 and 7 analyze the sensibility of the increase in productivity necessary to adopt the new technologies (some scenarios of impact on cost $\beta(t)$ are additionally considered).

Figures 6 and 7 suggest three assumptions regarding the necessary conditions for the adoption of new technologies: i) the increase in productivity required to adopt technologies decreases as the price of maize rises; ii) the increase in productivity required for the adoption of technologies decreases when the degree of agricultural production development is higher; and iii) in a low performance setting, a relatively higher impact on productivity is required for the adoption of the new technology, regardless of its cost.

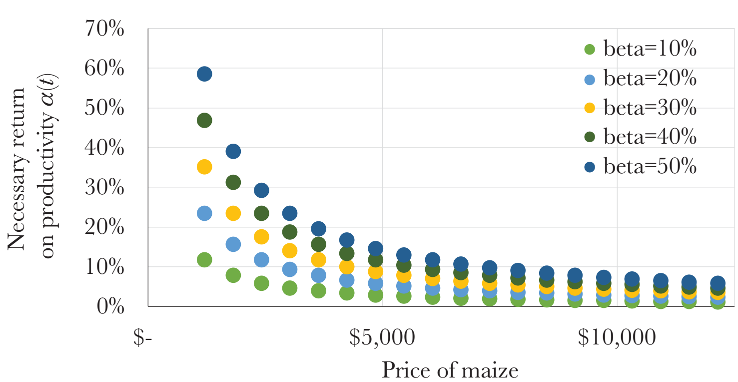


Figure 6. Isoquants for price of maize/return on productivity

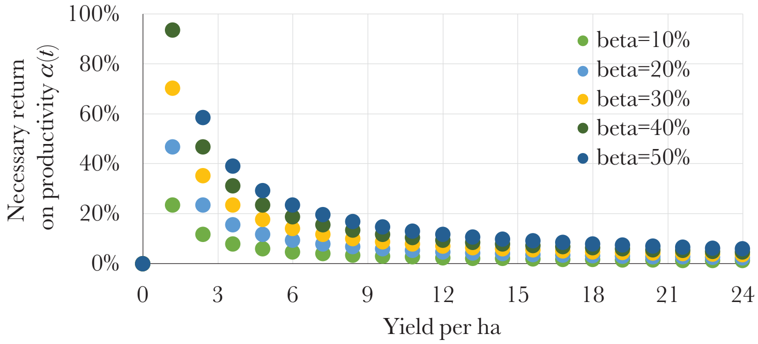


Figure 7. Isoquants for yield of maize/return on productivity.

Access barriers: infrastructure, technology, and capacities

As we already illustrated, the potential demand of digital technologies depends on different factors, such as geographical characteristics, level of mechanization, yield rate of the agricultural production units. All of these factors assume that attracting said technologies to the production setting is feasible. However, this is only possible if the minimal operation and adoption conditions required for the new technologies to perform are in place. As we have already mentioned, new technologies use cloud computing, the Internet of Things, and other digital devices that require basic access elements. Three relevant dimensions are analyzed below.

I) Telecoms infrastructure: access to 3G and 4G services.
II) Educational level, and use and adoption of ICT.
III) Mechanization of agricultural labor.

Infrastructure

The 3G and 4G mobile coverage is an enabling element for both tangible and intangible technologies, for the latter require data to be collected in the field and then sent to data centers to be processed. Although many service providers have set up capacities to save information and then exchange it when connectivity services are accessed (GSMA, 2019), this issue continues to be a natural barrier to the adoption of the technologies described. According to the Instituto Federal de Telecomunicaciones (IFT) and the Secretaria de Agricultura y Desarrollo Rural (SADER) 2020, 81% of agricultural production units in Mexico report having access to 3G technologies, while 75% of them report having access to 4G technologies. The percentage of production units (PU) with access to this service in the states of Oaxaca, Guerrero, Campeche, and Quintana Roo is the lowest of the country. On the contrary, as shown in Figure 8, production units in the northeastern and western states of the country report a higher access to this service. Figure 12 shows that the states whose production units have larger agricultural work areas usually have a higher level of 3G and 4G connectivity and coverage.

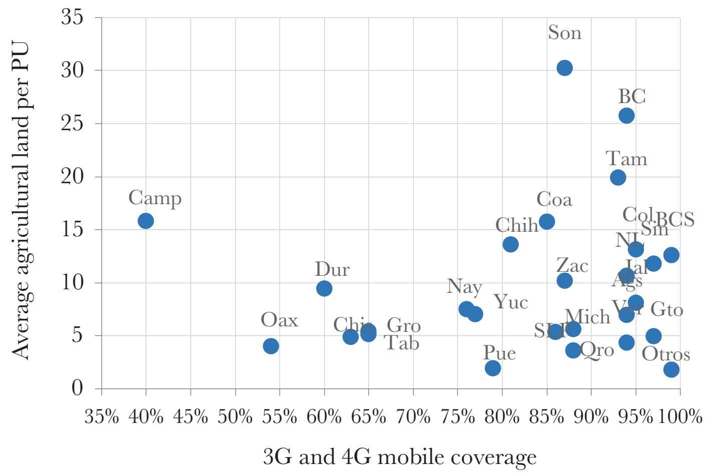


Figure 8. Average agricultural land according to their coverage level.

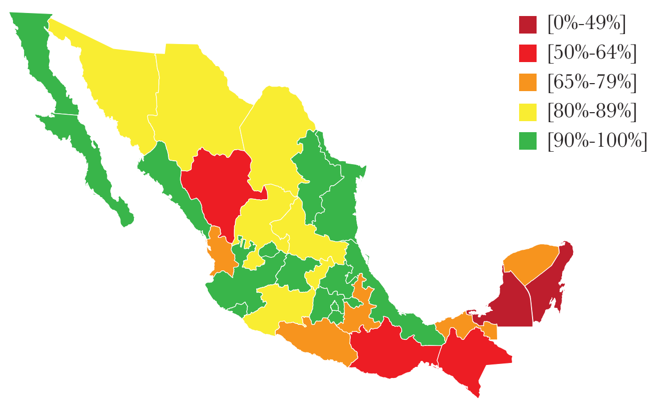


Figure 12. States according to their mobile coverage level.

Educational level, and use and adoption of ICT

The producer's or production unit owner's educational level is another aspect that restricts the demand for technologies, particularly those requiring digital interaction, such as remote consultancy or digital assessment apps. There are two types of abilities: basic education abilities, that allow the interpretation of figures and texts associated to crop development; and abilities that allow the use and adoption of communication and digital technologies. According to the Encuesta Nacional Agropecuaria (ENA, 2019), the average schooling level of agricultural producers is 5.9 years: 57.1% of producers have primary education, 16.8% have secondary education, and 14.8% do not have any studies. The states of Baja California (1.7%), Durango (2.1%), Mexico City (2.8%), and Aguascalientes (3.1%) have a lower percentage of uneducated producers, as can be seen on Figure 13.

Figures 9 and 10 show that states where production units have larger work areas are related with both a lower educational lag and a higher use of ICT. When

Figure 13. Educational level in Mexico (% of producers with no studies).

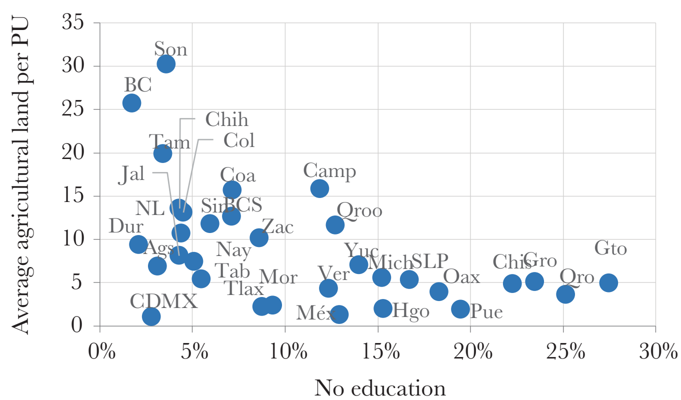


Figure 9. Average agricultural land according to the owner's educational level.

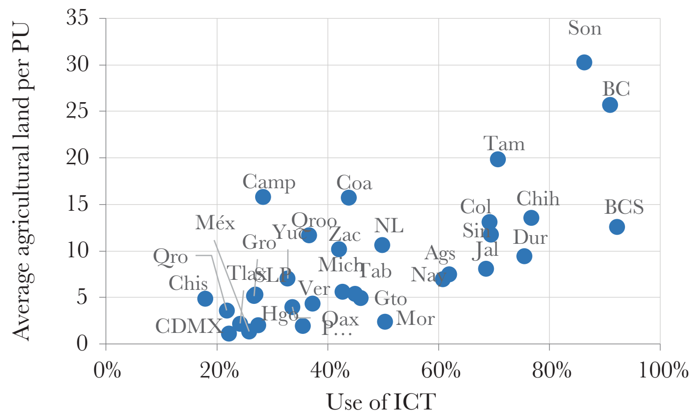


Figure 10. Average agricultural land according to use of ICT.

analyzing the producer's income in relation to the use of ICT in Mexico, we obtain a Pearson correlation coefficient of −0.7, which means that the larger the population[7] with incomes below the poverty line (PL), the lower the use of ICT.

[7] Living in municipalities with agricultural production units.

Mechanization

One of the main variables related to the potential demand of tangible technology is the level of mechanization of the production units. In this regard, the tractor is one of the more representative agricultural devices due to its versatility based on the large amount of implements it can use. According to ENA 2019 data, the higher percentage of production units that own a tractor are located in the northern, western, and northeastern states. In contrast, less than 40% of production units in most southern and southeastern states have tractors. This makes them less likely candidates to adopt tangible or embodied technologies, as Figure 14 shows.

The index of technology adoption potential is presented next in order to add in one dimension the basic conditions for the adoption of agriculture 4.0 technologies for each state of the country.

Figure 15 shows the geographic contrast between the northern, northeastern, and western production units, and those of the southern and southeastern regions with regard to their new technologies adoption potential. This evidence suggests the need of public policies to keep the new technologies from becoming a factor in further dividing the regions in terms of productivity.

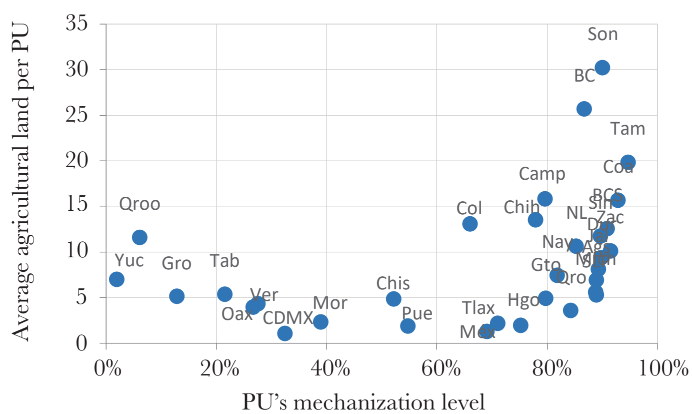


Figure 11. Average agricultural land according to PU's level of mechanization.

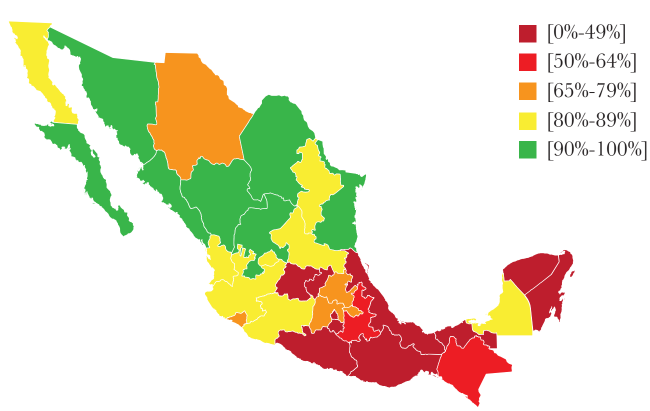


Figure 14. Mechanization level in Mexico.

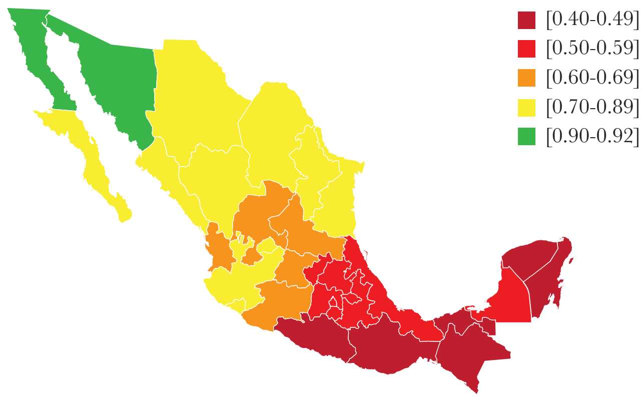


Figure 15. Index of technology adoption potential. (arithmetic mean)

Potential public policy actions to promote the adoption of new agriculture 4.0 technologies in Mexico:

Following the ideas that we have hitherto set out, we can offer a general outline of public policy actions that would, on the one hand, expand the offer of technology services and, on the other, foster their demand. In all cases, this development would take place within a regulatory framework that would encourage a more suitable adoption environment in the long run.

Fostering the conditions for supply

Course of action no. 1: Reducing the barriers between technology providers and the agricultural producers that currently operate in Mexico and could potentially receive the benefits of technological services related to the concept of agriculture 4.0.

- Promoting public-private alliances where public entities concentrate and order relevant information on rural production units according to their characteristics and make this information available to the private sector in exchange for benefits in the supply conditions of their services among the abovementioned production units.
- Including technology services of specialized companies in promotion programs that are currently on place, in order to enhance the value offered to producers and to tangibly expand the knowledge and benefits of new technologies among producers.
- Reducing the access barriers to the offer of technology services by concentrating the providers in a common marketplace.

Course of action no. 2: Encouraging the acquaintance with the offer of new technologies

- Generating public access information reports on service providers and periodically updating them so that they can serve as a radar for new technologies in the country.

- Validating the benefits of the new technologies either by fostering pilot tests within the private sector or through controlled tests in public facilities.
- Disseminating the benefits resulting from the use of new technologies in each agroecological region by encouraging the transmission of knowledge among producers or through public-access specialized dissemination seminars.
- Conducting pilot tests on the usage of new technologies subsidizing the adoption cost for the producer in order to tear down the cultural barriers to adoption with regard to the traditional production practices.

Course of action no. 3: Encouraging innovation and creation of infrastructure in Mexico

- Organizing seminars or awards revolving around the innovation or acceleration of new technologies in order to foster the research and development of said technologies in Mexico, with special emphasis on solving the idiosyncratic conditions of the country's productive regions.
- Facilitating the investment in infrastructure in Mexico by offering to share the risk and financing capital for development with the offerors.
- Creating public databases that enable the development of value-added services by providers whose size or condition is limiting, thereby allowing an even ground among providers of technology services.

Fostering the conditions for demand

Course of action no. 4: Investing in abilities and infrastructure to establish the necessary conditions for the adoption and development of new technologies in areas where said conditions are insufficient.

- Setting an agenda of digital inclusion and adoption of new technologies in the agricultural sector through the extension channels currently available in our country. Using the infrastructure and capacities of the public and private research and development centers of the country to consolidate them as technology transfer agents in each region: FIRA's Centros de Desarrollo Tecnológico (CDT); Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP); Centro Internacional de Mejoramiento de Maíz y Trigo (CIMMYT), etc.
- Investing in basic connectivity infrastructure.

Course of action no. 5: Reducing the adoption threshold for new technologies

- Pairing the adoption of new technologies with other traditional measures to increase productivity, thus securing the benefits of adopting digital technologies.
- Encouraging the adoption of new technologies by having an additional impact on the reduction of production costs where new technologies are involved, or else by reducing the adoption cost.

Conditions of governance and regulation of new technologies

Course of action no. 6: Consolidating a climate of certainty for investors and users of new technologies by creating and implementing an adequate regulation that establishes the rights and responsibilities of adopters, particularly regarding the information that results from the constant monitoring of the production processes with the new technologies.

Course of action no. 7: Working on the creation of a governing research and development center that convenes the public, private, and academic sectors for the introduction of new technologies in order to facilitate the adoption of agriculture 4.0 in Mexico, particularly in the less developed regions of the country.

CONCLUSIONS

This research has offered a general view of the current situation of agriculture 4.0-related technologies in Mexico. Agriculture 4.0 is a recent concept in academia and is recognized as a new paradigm with regard to previous technological changes in agriculture.

The offer of providers corresponds to the nature of Mexican agriculture, inasmuch as it focuses on maize, wheat, and bean as the main crops for the adoption of technology. We also identified that the demand for these technologies is heterogenous among the country's regions; it depends on the type of crop, the regions' characteristics, the prices of the products, and the natural barriers to access. Some ideal characteristics for the adoption of technologies are observed among the northern, northeastern, and western states: their production units are larger, they have a greater level of 3G and 4G connectivity and service coverage, their use of ICT and level of mechanization is higher, and the educational lag among their producers is lower.

For this reason, creating the necessary conditions for producers to adopt and continue developing digital agriculture is essential. According to our results, it is possible to present a general outline of public policy actions that, on the one hand, will expand the offer of technology services and, on the other, will foster their demand within a regulatory framework, so that all this may contribute to reduce the technology adoption gap between the different regions of the country.

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