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ESTIMATION OF THE FOREST AREA REQUIRED FOR WATER SUSTAINABILITY OF AVOCADO IN THE SOUTH OF THE STATE OF MEXICO

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ABSTRACT

This study analyzes the relationship between forest cover and water supply required for avocado (*Persea americana*) cultivation, in order to determine a balance between these two; based on the "Water Yield" model, which makes it possible to quantify water production in a specific watershed. The results obtained enable establishing the amount of forest needed to provide adequate water supply for avocado, in the context of the growing demand for this agro-food product worldwide. In this sense, it is possible to outline the guidelines for reflecting on changes in land use in the territory, based on the switch to avocado cultivation, so that an alteration in water availability can be avoided. We conclude that in the southern region of the State of Mexico, considering the regulatory impact of forest, it appears that the proportion required to provide water to one hectare of avocado is 1.35 ha.

Key words: ecosystem services, productive restructuration of rural areas, water availability.

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INTRODUCTION

Water is a common asset, essential for ecosystems and human well-being of present and future generations that plays a fundamental role in a wide range of natural and social processes (Álvarez, 2023). However, the increasing pressure on water resources due to climate change, urbanization, intensive agriculture and other socioeconomic factors generates interest in the availability and quality of water, worldwide (Vuille, 2013). For these reasons, research on the sustainable management of water resources has become a priority for the scientific community and decision makers (Calixto *et al*., 2022). A fundamental aspect of this research was to understand and quantify the hydrological processes that influence water availability, as well as to identify effective strategies for its conservation and efficient use, within the framework of avocado production systems, this being an agri-food commodity[3], recognized for its elevated water requirement compared to other crops (Borrego and Allende, 2021). This water demand is not only due to the characteristics of the crop itself; besides these changes in land use, water management by producers and edaphoclimatic elements must be taken into account, as these are essential to evaluate their sustainability.

Thus, this article intended to evaluate water yield in the Cutzamala River sub-basin, among the avocado orchards of a small-scale producer association called "La Libertad", as it relates to the extent of forest. To do so, we applied the "Water Yield" model, in its interface within the Geographic Information System (GIS) TerrSet 2020; a tool that has the potential to become a novel methodology for planning agriculture in rural territories, because it enables assessing changes in water production, depending on different land use in the territory.

We also analyzed the actors, factors, laws and policies that have intervened in the modification of land use and land cover, resulting in the alteration of water yield over the years. The theory is that by advancing understanding of these complex interactions, it is possible to contribute to the development of water resource management policies that promote environmental sustainability and long-term human well-being in the context of climate change.

This text is composed of five parts. Following this introductory section, a theoretical discussion is included, which establishes different approaches to the models of diagnosis and quantification of water resources, introducing a debate between spatial representation and sustainable water management. Subsequently, the methodological design of the research is expressed mathematically, followed by the analyzed results, from a water yield model over two historical periods. The discussion of the results is presented below, highlighting the political-economic context as a basic condition for understanding the implications of the water sustainability of avocado cultivation in the context of neoliberal and market economies. We conclude by indicating that this article contributes by identifying that the proportion of forest to support one hectare of avocado is 1.35 ha. However, this does not imply that this can be adopted as a universally valid generalization, but rather illustrates that the contextual meaning of water availability relates to the proportion of forest as opposed to agriculture, highlighting the need to develop further research projects in order to include a variety of avocado-producing territories, to provide a range of comparative analyses.

THEORETICAL FRAMEWORK

In the academic field, various models have been developed to evaluate and quantify water resources. Nkwonta *et al*. (2017) built a water resource management model for reservoirs based on three other models: the water yield model, the planning model, and the quality model. For the authors, the purpose of this process is to "balance the water resources available in a system with water requirements and losses, which affect the system" (Nkwonta *et al*., 2017: 110). It is important to emphasize this intention, as this research relied on the ecosystem services model "Water Yield" to estimate the difference in water yield between one hectare of avocado and one hectare of forest.

Similarly, Song *et al*. (2015) carried out the evaluation of ecosystem services by applying the InVEST model, for the quantification of water resource supply services in forest ecosystems in South Korea. However, due to the lack of updated data for the study area, the authors mention that the results were not precise, complicating decision-making. They also point out the need to combine quantitative and qualitative approaches for the evaluation of ecosystem services, in order to understand the phenomena in a more holistic way. Firstly, they suggest using models such as SWAT (Soil and Water Assessment Tool) and VIC (Variable Infiltration Capacity), whereas, for the qualitative approach, the comparison and evaluation of functions was based on the functional classification of the Korean forest service.

Complying with this idea, Scordo *et al*. (2018) state that the collection of data to model watersheds in a reliable way is a critical aspect for public policy decision makers to improve the supply of drinking water, energy production and recreational services, as well as to predict the possible results of modifications in precipitation patterns or extreme climate changes. In the research by Scordo *et al*. (2018), 749 North American watersheds were grouped into five groups according to nine environmental variables, which were modeled according to the InVEST SWYM (Seasonal Water Yield Model) and subsequently compared, in order to determine which variables most influenced results. We conclude that it is necessary to refer to cryospheric conditions, as these improve the results of the hydrological model in an environmental region under a low-elevation boreal subhumid climate. Besides this, evapotranspiration, solar radiation and slope are often oversimplified in hydrological models and require particular attention.

Research by Yang *et al*. (2020) and Rahimi *et al*. (2020) used the Integrated Valuation of Ecosystem Services and Trade-offs model to simulate water yield with reference to land use changes. In the first study, this model was used to analyze the Bosten Lake basin between 1985 and 2015, concluding that "water yield capacity, correlated positively with precipitation, is highest in grassland vegetation and lowest in cultivated and unused land" (Yang *et al*., 2020: 1035). The second study applied this to comprehend how land use changes affect the water ecosystem services of wetlands in southeastern Iran. Evidently, the capacity of wetlands to provide ecosystem services depends on biophysical characteristics related to natural and anthropogenic factors (Rahimi *et al*. 2020: 3715).

Likewise, using the "Land Change Modeler" of the Terrset 2020 software and the InVEST model, Shi *et al*. (2022) identified land use changes for the city of Shenzhen (China) and conducted an analysis between 2000 and 2010 that focused on the relationship between urbanization and the impacts it generates on food production, water and ecosystems. They concluded that habitat quality, water supply and crop production evidently decreased due to rapid urbanization. Contrarily, "an upward trend in water yield was identified, due to the increase in urban artificial surfaces, while the water yield of other land use areas, such as forests and grasslands decreased," (Shi *et al*., 2022: 6).

In Latin America, Minga's (2018) contributions and his analyses of the basins in southern Ecuador stand out. In this research, the InVEST Water Yield model was used, which is based on Budyko's hydrological framework and considered variables such as precipitation, land use/cover, actual evapotranspiration, soil depth and water content available to plants. This model was applied to nine watersheds in the period between 1970 and 2015, making climate change projections for the decades 2030, 2050, 2070 and 2080. The results predict that water yield will increase in the middle and lower areas of the watersheds, whereas in the upper areas of the basins that originate in the Andes mountain range, a reduction in water production is expected. (Minga, 2018: 93).

For the Mexican case, Felipe (2023) uses the InVEST Seasonal Water Yield model to estimate the economic value of water for the Cajonos River basin in Oaxaca. He argues that this evaluation allows us to quantify, in monetary terms, the benefit that society receives from this ecosystem service. The results obtained show a local recharge of up to 1,625 mm throughout the basin. In addition, the areas with the lowest and highest recharge were located, and the characteristics that define the difference in recharge in each area were identified. Using this, "we estimated an economic value for the water resource within the basin, obtaining a monetary range of 1,164.92 USD/m3 to 3,485.77 USD/m3" (Felipe, 2023: 47).

Lovera *et al.* (2018) carried out an evaluation of ecosystem services in the municipality of Valle de Bravo, a region that is important for the State of Mexico in terms of forestry and water, as it forms part of the catchment area of the Cutzamala System, responsible for providing part of the drinking water for Mexico City. The evaluation was carried out based on a comparative analysis of land use and vegetation during the period between 1994 and 2016, to identify the effects of changes in land use on the water yield of the area. Results indicated that temperate forests still persist throughout most of the municipality; however, urban areas have doubled, causing an increase in water yield. They mention that these results may be useful in environmental planning and land use programs.

In the research discussed here, at least three important aspects are evident. Firstly, the participation of communities in the hydrological estimation processes is practically non-existent; apparently everything is very technical and the idea that water planning in the territories is a matter exclusively for technicians and politicians still persists. Secondly, the lack of data in some study areas does not facilitate precise analysis and validation of models, meaning that results must be approached with caution in terms of decision-making. Finally, although the research makes claims for the usefulness of its results in territorial water planning, none of these develops concrete planning proposals based on the results obtained. In this research, the use of the Water Yield model and its results will be essential to determine how much forest is needed to ensure adequate water for avocado orchards, and thus, contribute to the construction of Water Management Models for Agriculture (MOGHIPA). This in turn can help, together with the multiple actors involved, in the planning, management and evaluation of water use for this and other crops.

METHODOLOGY

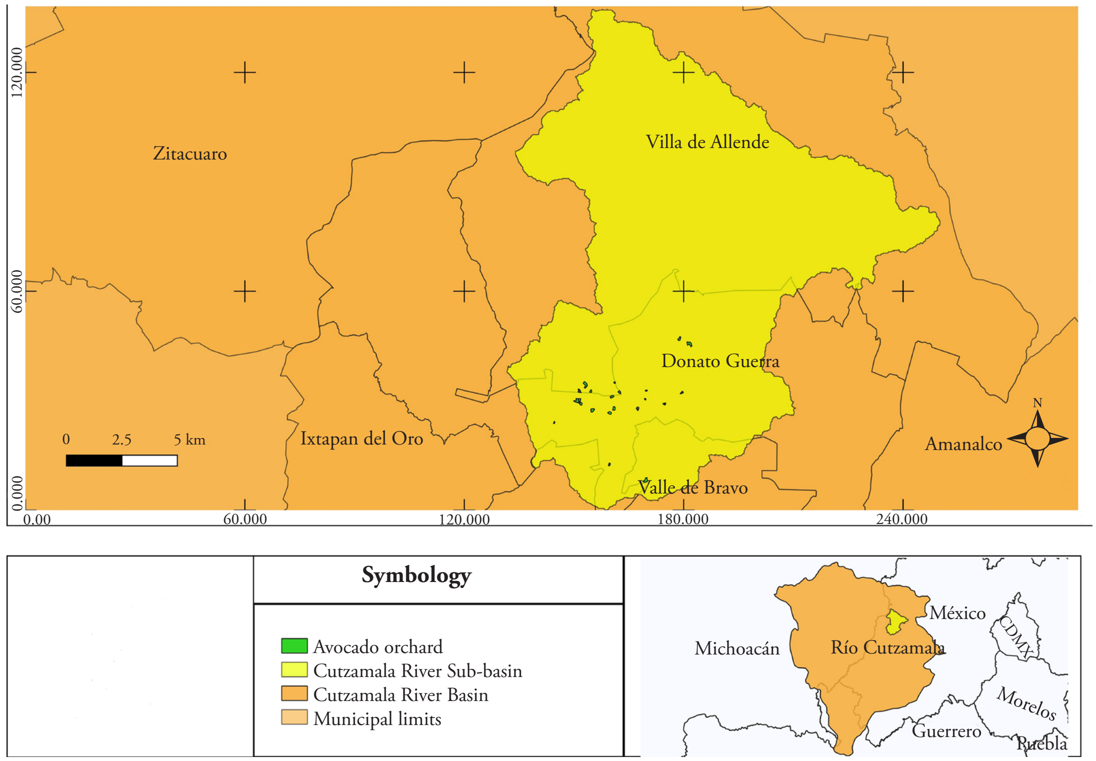
Hydrological models represent an indispensable tool for analyzing and monitoring the benefits and impacts produced in nature derived from economic activities. One of these models is the "Water Yield" model, which provides the possibility of calculating the water yield of a specific area, pixel by pixel, in order to identify water production in a watershed. It also identifies the different yields, depending on use and land cover. This method made it possible to compare the values between the areas dedicated to forests and those dedicated to avocados to establish relative quantities for both during two specific time periods, 1986-2003 and 2004-2021.

The study area is located in the Cutzamala River basin and was delimited using the "Watershed" tool of Terrset 2020 software, taking into account the runoff in the area and the location of the avocado producers of the "La Libertad" association, which is made up of small-scale producers from the southern region of the State of Mexico (Figure 1). The boundaries of the sub-basin are distributed between the municipalities of Villa de Allende, Donato Guerra, and Valle de Bravo.

Water yield model

The International Glossary of Hydrology defines water yield as the "quantity of surface or groundwater in a basin that can be obtained for a particular use during a defined time interval" (World Meteorological Organization, 2012: 382). Therefore, retrieving data on the water yield of a basin can be considered as a reference point with respect to surface water runoff, essential for any planning procedure for territories in terms of water, especially when the concern is agriculture.

We decided to use the ecosystem services model "Water Yield" InVest version 19.0.8 (Natural Capital Project, 2022), which estimates the average annual water runoff as follows:



Source: Self-elaborated by the authors with data from the National Commission for the Knowledge and Use of Biodiversity (Conabio) and with Terrset Software 2020.
Figure 1. Cutzamala River Subbasin.

$$Y_{xj} = \left(1 - \frac{AET_{xj}}{P_x}\right) \times P_x$$

where AET_{xj}: represents the actual annual evapotranspiration at pixel x within land cover type j; P_x: is the average annual precipitation at the same pixel.

The AET_{xj}/P_x fraction is an estimate of the Budyko curve (Minga, 2018), which reflects the partitioning of evapo-transpiration within the water balance (Eastman, 2020). This fraction is calculated using a Rxj dryness index and a dimensionless ωx parameter, which indicates the relationship between the water content available to plants and the expected precipitation during the year. The dryness index R_{xj} is determined by the relationship between the product of vegetation evapotranspiration, the evapotranspiration reference, and annual precipitation (Eastman, 2020). Other data needed to calculate water yield include soil depth (mm) and plant available water content

(PAWC). PAWC is defined as the ratio of water holding capacity (the amount of water retained between the soil's field capacity and wilting point) that can be absorbed by a plant, also known as available water content in millimeter units (Natural Capital Project, 2022).

Data collection

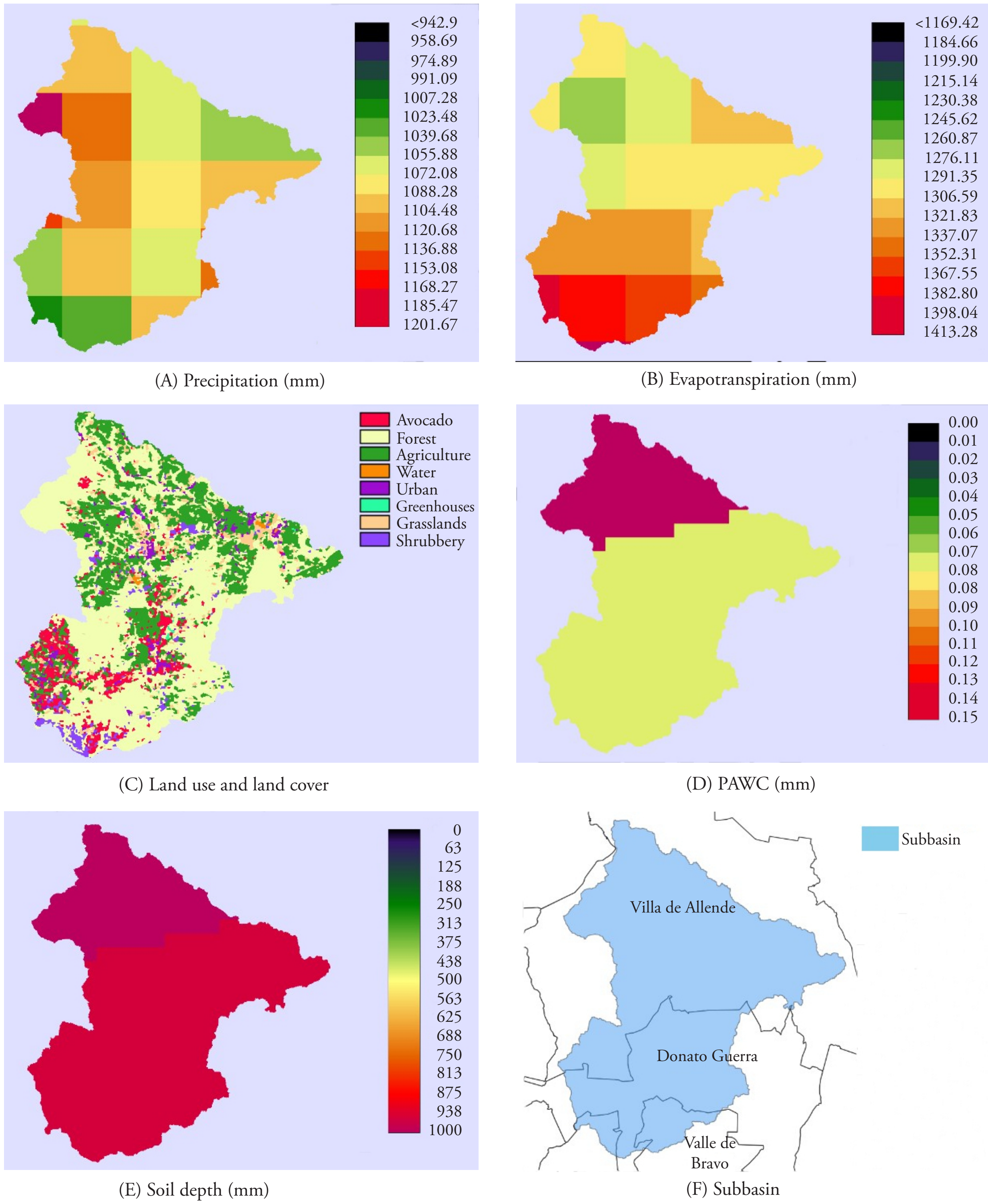
To delimit the watershed and generate the digital elevation map (DEM), we used images from the *Shuttle Radar Topography Mission* (SRTM) 1 Arc-Second Global, obtained through Earth Explorer. This dataset offers global coverage with a resolution of 1 arc second (30 meters), and was downloaded in Geotiff format for further processing. In addition, a biophysical table was prepared in CSV format, containing the attributes of each land use category. The runoff coefficient (*Kc*) and root depth values were taken from bibliographic sources, specifically from Allen *et al*. (1998) and Sharp *et al*. (2018), respectively.

To generate the land use and cover maps, satellite images from the United States Geological Survey (USGS) from 2003 and 2021[4] were used, through Landsat 7 ETM+C2 L2 for the year 2003 and Landsat 8-9 OLI/TIRS C2 L2 for 2021, and a supervised classification was carried out, using the software's "segmentation" and "segtrain" tools, which allowed the images to be fragmented and specific land uses to be defined.

To obtain annual precipitation, evapotranspiration and temperature, Terraclimate data were used, divided into two periods, each of 18 years, 1986-2003 and 2004-2021, and subsequently, the "Earth Trends Modeler" tool from TerrSet was used to create time series of the three variables for the two periods analyzed. These data provide detailed information on the spatial and temporal distribution of the climatic variables. In the correction of the precipitation and evapotranspiration data, a multiplicative factor of 0.1 was applied.

Likewise, the soil depth image was obtained from the Harmonized World Soil Database (HWSD) version 2.0 at a resolution of 30 arc-seconds, which provides information on the depth at which root penetration is strongly inhibited, due to the physical or chemical characteristics of the soil. Finally, the image for plant available water capacity (PAWC) was generated using the same HWSD database, the study area was located and the corresponding values were taken, then this was calculated by dividing the AWC (available water capacity, in cm) and the Depth (soil depth, in mm), these values represent the fraction of the water content available to the plant in millimeters and range from 0 to 1; these are dimensionless. To illustrate the above, we present the images used to run the "Water Yield" model for the period 2004-2021 (Figure 2).

Data analysis focused on comparing the results, as a percentage, of the water yield, between the soils used for avocado cultivation and the forests in the area.



Source: self-elaborated in Terrset 2020

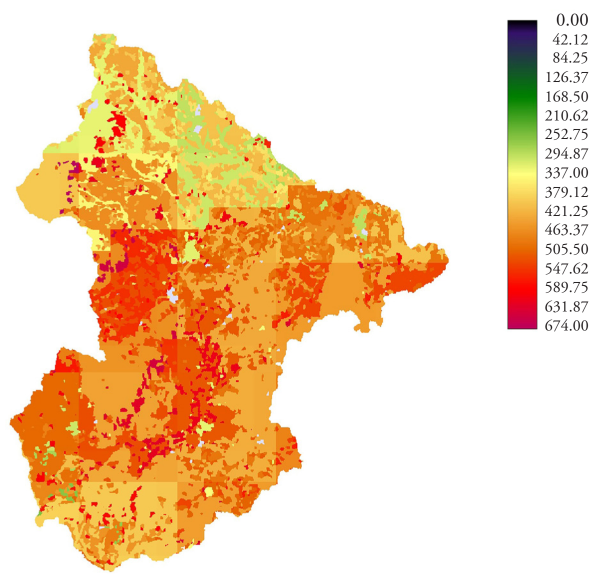
Figure 2. Data used for the “Water Yield” model for the 2004- 2021 period.

This, with the aim of determining their water differences and estimating the amount of forest needed to provide water support to one hectare of avocado.

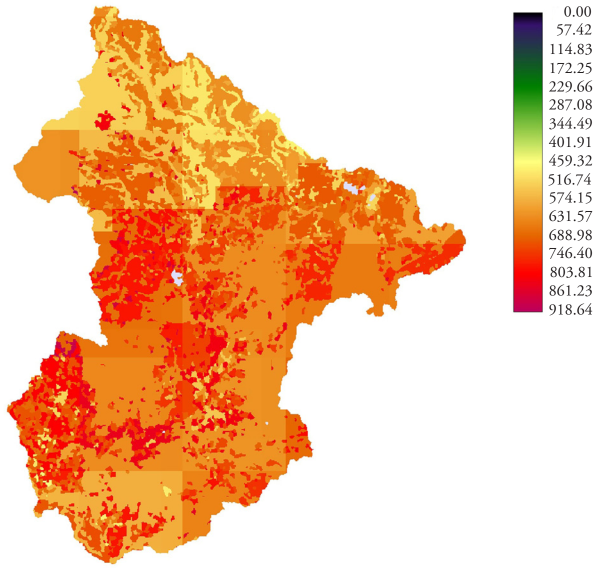
RESULTS

Model results produced two images of water yield in units of millimeters for the periods 1986-2003 (Figure 3) and 2004-2021 (Figure 4). These make it possible to compare not only the differences in water production in the sub-basin, but also to observe changes in the behavior of land use, a variable that is relevant for analyzing hydrological aspects.

The results of water yield broken down by land use and cover for the two periods are presented in Table 1, where an increase is observed for the period 2004-2021, due to changes in land use and cover, as well as the increase in artificial surfaces. In the first period, avocado represented 4.9% of the total area of the sub-basin and manifested the highest water yield with 19.6%, a position that is maintained during the second period, despite a reduction in the percentage of water yield, but with an increase in the planted area, resulting in 7.8% and 17.7% respectively. For its part, forest cover showed a significant increase, going from 46.2% in 2003 to 53% in 2021, however, this increase was not reflected in water yield, as it practically remained at 13% and 13.1% during those years. This indicates that forests are excellent water regulators and enable stable flows to be maintained in terms of water sources.



Source: self-elaborated in Terrset 2020.
Figure 3. Model for Water Yield (mm) for the years 1986-2003.



Source: self-elaborated in Terrset 2020.
Figure 4. Model for Water Yield (mm) for the years 2004- 2021.

The area devoted to agriculture decreased from 32.4% to 26.6%, indicating changes in land use in the area, as avocado orchards gradually occupied the spaces that were previously devoted to cornfields (maize), broad beans or peas. Water yield went from 15.7% to 15.3%. Likewise, a reduction in water in the sub-basin is observed, as it occupied 0.5% in the first period and only 0.2% in the second, which is also a manifestation of the problems of water scarcity, aggravated by economic activities and climate change.

Table 1. Results from the Wy (Water yield) model for the two periods analyzed.

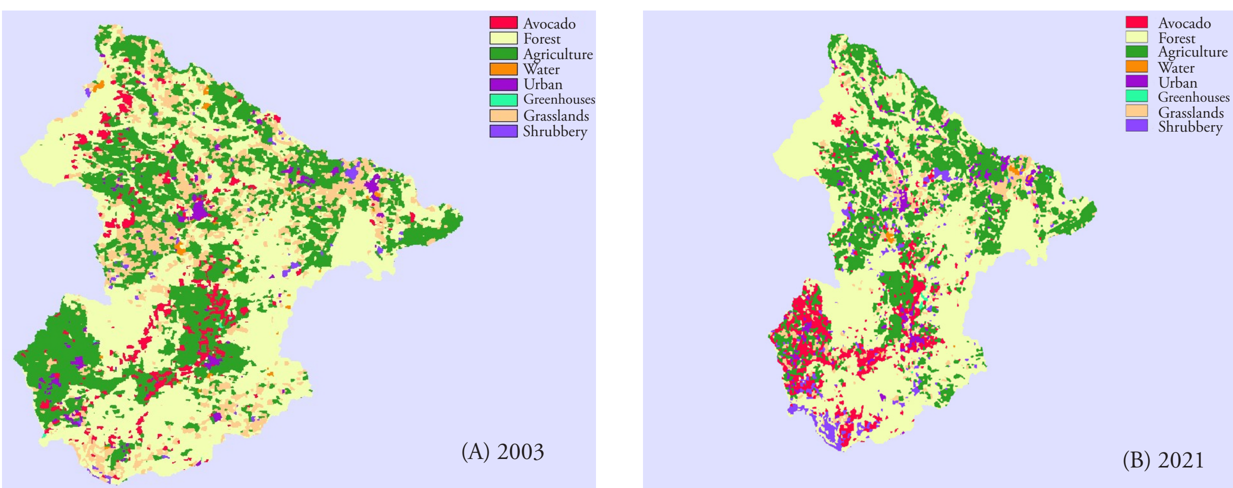
Use and land-cover	1986-2003		2004-2021	
	Area-km^2 (%)	Wy-mm (%)	Area-km^2 (%)	Wy-mm (%)
Avocado	10.85 (4.9%)	611.23 (19.6%)	17.21 (7.8%)	816.99 (17.7%)
Woodland	102.37 (46.2%)	404.62 (13 %)	117.57 (53%)	605.69 (13.1%)
Agriculture	71.79 (32.4%)	489.79 (15.7%)	58.99 (26.6%)	706.22 (15.3%)
Water	1.01 (0.5%)	N/A	0.50 (0.2%)	N/A
Urban	3.78 (1.7%)	311.77 (10 %)	5.85 (2.6%)	542.51 (11.7%)
Greenhouses	0.12 (0.1%)	305.32 (9.8%)	0.27 (0.1%)	540.42 (11.7%)
Pasture	30.23 (13.6%)	459.65 (14.8%)	14.81 (6.7%)	669.46 (14.5%)
Shrubs	1.66 (0.8%)	528.40 (17%)	6.63 (3%)	744.32 (16.1%)

Source: self-elaborated with data from TerrSet 2020.

Urban areas and greenhouses have also expanded and their water yield for 2021 was 11.7% for both periods. This is because they are artificial surfaces and many of them are impermeable, which impedes water infiltration. The area dedicated to grasslands, whether sown or natural, decreased, going from 13.6% to 6.7%; this change is mainly due to the increase in agricultural crops in areas where there were previously pastures. Finally, shrubs occupied 3% of the total area of the sub-basin in 2021 with a yield of 16.1%. These changes can be observed in the Figure 5.

Subsequently, after observing the changes in land use and water yield, the total volume for each category was obtained, as presented in Table 2.

The final result derived from the model is shown here, but as the aim is to compare the volumes from the forest with that of the avocado orchards, it is necessary to convert the area in square meters (m^2) into hectares (ha), and then divide it by the water yield in cubic millimeters (mm^3) (Table 3). This process was only carried out for the second period of analysis, as this is the most recent. Based on water yield data in mm^3 per hectare, we calculated the proportion of each land use and ground cover compared to forest, concluding that 1.35 ha of forest are needed to provide water to maintain 1 ha of avocado; 1.17 ha for 1 ha dedicated to agriculture; 1.11 ha for 1 ha of pasture and 1.23 ha for 1 ha of shrubs. Thus, taking into account that the producers' association is carrying out reforestation activities and currently has 36.5 hectares of avocado in production, it is estimated that they need to reforest 49.2 hectares of forest to provide water to maintain their orchards.



Source: self–elaborated in Terrset 2020.

Figure 5. Land use and ground cover for the two periods analyzed.

Table 2. Water yield by volume depending on land use and ground cover.

Land use and ground cover	1986-2003		2004-2021		1986-2003	2004-2021
	Area (m^2)	Wy (m)	Area (m^2)	Wy (m)	Vol (Mm^3)	Vol (Mm^3)
Avocado	10,851,031	0.611	17,206,929	0.8170	6.632	14.058
Woodland	102,369,212	0.405	117,574,352	0.6057	41.421	71.214
Agriculture	71,786,827	0.490	58,988,281	0.7062	35.161	41.659
Water	1,013,123	N/A	495,308	N/A	N/A	N/A
Urban	3,784,118	0.312	5,850,793	0.5425	1.180	3.174
Greenhouses	116,006	0.305	268,818	0.5404	0.035	0.145
Pasture	30,233,727	0.460	1,480,7124	0.6695	13.897	9.913
Shrubs	1,664,084	0.528	6,626,523	0.7443	0.879	4.932

Source: self–elaborated with data from Terrset 2020.

DISCUSSION

Modifications in the land use of a territory directly affect its water yield (Lovera *et al*., 2018), so that this effect, represents an important aspect for agricultural sustainability, as shown by the results from this work. Alterations in hydrological yield are the result of multiple factors, not only edaphoclimatic, but also political, cultural and economic, aspects that are revealed in the calculations obtained for the case studied.

Table 3. Comparative proportion of water yield between forest and other land uses.

Land use and ground cover	2004-2021		ha	mm3	Proportion
	Area (ha)	Wy (mm3)			
Avocado	1,721	14.058	1	0.008	1.35
Woodland	11,757	71.214	1	0.006	1.00
Agriculture	5,899	41.659	1	0.007	1.17
Water	50	N/A	1	N/A	N/A
Urban	585	3.174	1	N/A	N/A
Greenhouses	27	0.145	1	N/A	N/A
Pasture	1,481	9.913	1	0.007	1.11
Shrubs	663	4.932	1	0.007	1.23

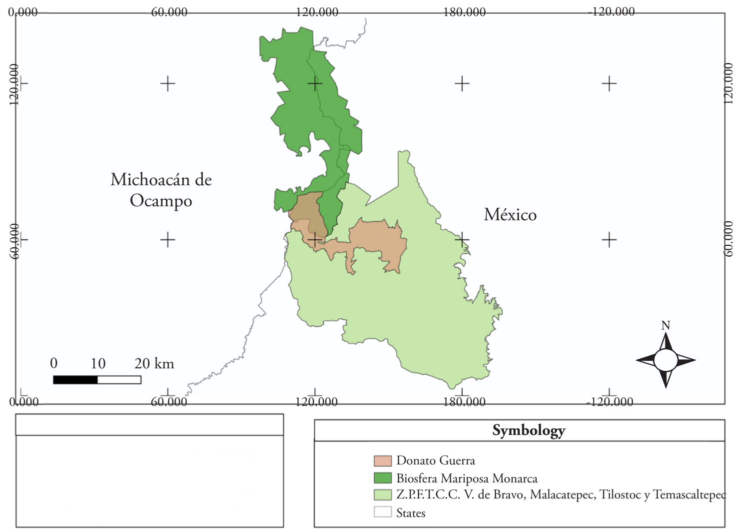
Source: self-elaborated with data from TerrSet 2020.

One of the factors that has most influenced changes in land use in Mexican territory are the free trade agreements, especially NAFTA, signed in 1994 between Canada, the United States and Mexico, and updated in 2018 by T-MEC. Authors such as Hernández (2021: 1122) affirm that due to its "neoliberal character in Mexico, little was gained and much was lost in free agricultural trade with the United States and Canada", this, due to the asymmetries in the productive and technological structure, subsidized agricultural production in those countries and dumping[5]. In the specific case of avocado production and the transformation of territories for its monoculture, there is an important relationship in terms of the configuration of this product as an agri-food commodity, in the context of the neoliberal logistic of agro-exportation.

Besides this, the gradual elimination of tariffs on imported agricultural products caused a considerable part of the Mexican peasant economy to be affected by the entry of large quantities of food at lower prices, which resulted in their crops becoming unprofitable (Escalante and González, 2018). This phenomenon was also evident in the municipality of Donato Guerra, where so many farmers and producers went from growing peas, corn and beans to planting avocado as a crop for export that would generate higher income (Martínez, 2019), but which unfortunately also contributed to the current water crisis in the area.

In addition to international treaties, there are elements at the national level that directly or indirectly, provoke changes in land use. One of the most important was the 1992 reform to article 27 of the Mexican Political Constitution (Gómez, 2016), which allowed the privatization of communal and ejidal lands in the country, transforming agrarian structure and the land tenure regime. This reform was also interpreted as the process of neoliberal modernization of the Mexican countryside by authors such as Ita. A. (2019), who considers this to represent the starting point for the dispossession of communal lands and assets, opening the way to the complete reconfiguration of territories towards monoculture, and specialized and export-oriented production models. This aspect is reinforced by the availability of financial resources and the acquisition of new knowledge held by actors who emigrate to the United States and who strongly influence the reconfiguration of the territory, by their remittance contributions.

Importantly, in Donato Guerra, two protected natural areas (ANP) were declared that represent federal conservation projects (General Law on Ecological Balance and Environmental Protection-LGEEPA, 2023). These are "The Monarch Butterfly Biosphere Reserve" and the "Forest Protection Zone of the Lands Constituting the Basins (F.P.Z.L.C.B.) of the Valle de Bravo, Malacatepec, Tilostoc and Temascaltepec rivers". Both cover the entire municipal territory, as apparent in the Figure 6.



Source: self-elaborated with data from Conabio.
Figure 6. Conservation areas under the jurisdiction of the municipality of Donato Guerra-State of Mexico.

The results obtained are useful for understanding the changes in land use in Donato Guerra, in the context of the productive restructuring of the territory, emigration and territorial management; strategies rooted in conservation. In the case of the declaration of the Monarch Butterfly Biosphere Reserve, the smallest in area in the municipality, it is possible to identify an agenda for territorial reconfiguration, based on a diagnostic procedure (Secretariat of Environment and Natural Resources-SEMARNAT, 2001), which articulates flexible sub-zones with a relatively limited portion of a buffer or restricted use sub-zone that prohibits any change in land use, all of these complying with a sustainable outlook (SEMARNAT, 2000), but always framed in a prescriptive viewpoint aligned with international agenda. The persistence of illegal logging represents an example of this flexible and fluid restriction, which affects around 23,600 hectares of forest per year (SEMARNAT, 2001). The above, in addition to causing serious damage to the flow of water bodies, constitutes the starting point for the reconfiguration of land use, initially towards agricultural activities, but eventually towards urban use.

For its part, the Forest Protection Zone of the Lands Constituting the Basins of the Valle de Bravo, Malacatepec, Tilostoc and Temas-caltepec rivers aims to protect the forest massifs that capture water in the hydrological basins where they originate (Comisión Nacional de Áreas Naturales Protegidas-CONANP, 2024), this territory being one of the main sources of water supply for one of the largest metropolises on the planet, by means of the Cutzamala System.

This indicates that although crops play an important role in the construction of hydrosocial territories, the case at hand reveals a crucial preceding conflict between rural and urban areas, which must be filtered through the concepts of social justice and historical memory, without overestimating the impact of crops on hydrological balance. A clear example of the institutionalization of the water conflict is the fact that the National Water Law gives priority to domestic use, particularly in urban contexts (Government of Mexico, 1992), ignoring the conditions of existence and specific needs of communities that are peripheral to water systems.

Although this reserve is essential for water supply, sub-zones were defined to establish which types of activities are permitted and which are not (Table 4). For this work, the so-called "Sustainable Use of Ecosystems in Agricultural Areas" sub-zone, which occupies 46.5% of the territory, is of particular interest. In other words, the zoning criteria applied have clearly oriented activities towards primary production. Of course, as specialized and export agriculture, specifically avocado, is a profitable activity, it is understandable that "the agricultural frontier has expanded with respect to the forest frontier, increasing water and soil pollution due to the intensive use of agrochemicals and pesticides, soil erosion and siltation of water bodies" (CONANP, 2024). It is important to understand that "agricultural growth and increasing demand for natural resources to supply the needs of the population have caused conservation areas to change over time" (Alvear, 2018: 20). However, it is very different to understand these transformations in the context of power relations, the reconfiguration of markets and an evident ecological crisis, which invites us to rethink the way in which water resources are managed and find possible solutions.

Table 4. Some activities that are allowed and not allowed within F.P.Z.L.C.B.

Subzone for sustainable use of agricultural and livestock ecosystems	
Activities that are permitted	Activities that are not permitted
-Agroforestry, silvopastoral and agrosilvopastoral activities	-Those that harass or harm wild species in any way
-Traditional cultural activities	-Expand the agricultural frontier by the permanent removal of natural vegetation
-Organic agriculture that does not expand the agricultural frontier	-Open new tracks or paths
-Non-timber forest exploitation	-Timber forest exploitation

Source: self-elaborated based on CONANP (2024).

As the agricultural and rural development policy of the State of Mexico had been configured, it can be understood that one of the main forces of transformation of land use is agricultural transformation based on the establishment of crops with greater economic profitability such as agave, coffee, some vegetables and avocados (Secretaría de Agricultura y Desarrollo Rural-SADER, 2020). The results make it possible to identify a benefit in the income of avocado producers, although this presents multiple contradictions such as overexploitation of water, the incidence of criminal groups and the emergence of new inequalities.

These projects have had a positive impact on the income of the beneficiary families and on the technological transfer of crops (SADER, 2020: 57). However, collected data indicate the need to make a more detailed evaluation of the achievements made in terms of environmental and social sustainability of this type of agrarian policy, especially when it induces a change to crops that demand more water and insert producers into new economic dynamics.

According to what was observed in the field, it is possible to perceive the ambivalence on the part of the ejidal committee concerning forestry use practices; they have permitted deforestation due to a greater extraction of cubic meters of wood than that allowed in the SEMAR-NAT-03-003-C procedure. The above reveals ambiguous areas, where the dynamics are dominated by criminal groups (Sáenz, 2018) and forest fires (Ruiz, 2022). This brings us once again to the starting point of this discussion, which stated that the water efficiency of the territories is a systemic, complex and multifactorial element, meaning it is pertinent to make specific calculations concerning concrete actions. In this case, we refer to the relationship between avocado production and water sustainability, as only by dealing with small aspects of complex problems, will it be possible to face the great challenges of the 21st century.

Many public policies and regulatory tools are based on the right concepts, however they are merely rhetorical, which is why it is essential to develop basic knowledge about agricultural production, water yield and land use transformation. It is also important that this knowledge be made available to decision-makers and producers, in order to move towards agricultural models focused on human well-being rather than the market. As apparent, this is only possible to the extent that inter-institutional and community work is articulated, for the benefit of long-term ecosystem conservation, and with it, the possibility of continuing to reproduce the life, culture and economy of the area.

CONCLUSIONS

Notably, considering the studies that have used the "Water Yield" model, none was found that did so with the purpose of determining a comparison between two types of land use. This allows establishing a water balance for different crops, in a context where the demand for water for agriculture is increasing. Likewise, it makes it easier for small-scale producer associations to measure the impact of crops and take actions that ensure long-term balance.

Similarly, it is necessary to critically reflect on the factors, actors and policies that intervene in the territory, often without taking into account the impacts that they can cause by modifying land use and, consequently, the water yield of the basin. Evidently, all the factors that influence changes in land use in the territory have a common matrix, which is the search for capital accumulation to the detriment of nature. For this reason, it is essential to carry out studies on the transformation of land use and vegetation cover, in order to determine the impacts and identify measures that should be implemented to avoid water scarcity and to conserve ecosystem services.

Finally, this research enabled establishing the proportion and water balance between the 36.5 ha of avocado in the association and the forest; indicating a need to reforest 49.2 ha. However, this proportion, which is 1.35 to 1, cannot be applied automatically anywhere in the country or the world, as it is necessary to perform an analysis of each particular context, in order to establish this proportion.

NOTES

[3]Although possibly an anglicism, the use of the word commodity allows us to differentiate some goods from others, according to the dynamics that develop around them. The avocado meets some of the key characteristics of commodities: it is a relatively homogeneous product, its value depends largely on international supply and demand, and it is subject to transactions in global markets.

[4]The last year of each period was selected because it allows us to observe the final result from changes in land use.

[5]Selling a product at a price lower than the one sold on the market, in an attempt to eliminate competition.

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