

Global exports draining local water resources: land concentration, food exports and water grabbing in the Ica Valley (Peru).

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Abstract

The agro-export boom is threatening the sustainability of water resources in many regions around the world. This is the case of the Ica valley in Peru, where in the last decades traditional agriculture has been replaced by big agricultural businesses to meet the growing international food demand. This has led to increasing land concentration by large exporting farms jointly with an increase in groundwater exploitation for irrigation. In this paper, we analyze the effect of land concentration, exporting crop specialization and irrigation intensity on groundwater sustainability using an econometric approach. Our findings highlighted an inverse relation between groundwater sustainability in terms of water withdrawal in the Ica Valley and the intensity of irrigation (drip technology), commodity specialization and concentration of large farms. More research is needed to fully understand the impacts of this very important economic activity on Peru's natural resources, to ensure its sustainability in the long term.

Keywords: Ica Valley, Water Grabbing, Land concentration, Rebound effect, Groundwater sustainability, Peru

[7669 words]

1. Introduction

Water scarcity affects about four billion people and is presenting major challenges both for society and the environment (De Angelis et al., 2017; Mekonnen and Hoekstra, 2016). There are many

factors, including climate change, population growth, desertification, and urbanization which put pressure on water resources, exacerbating water scarcity, especially in arid and semi-arid regions. Water scarcity challenges food security (Alexandratos and Bruinsma, 2012; FAO et al., 2015). Since the world's population will continue to expand (UNDESA, 2018), agriculture will need to overcome the challenges posed by water scarcity to avoid future famines, social disorder and instability, mass migration, and armed conflict (FAO, 2012, 2011).

Water is essential for food production and good water governance will be key for global sustainability. Irrigation is one of the major drivers of water consumption since it accounts for almost 70% of global freshwater withdrawals (Campbell et al., 2017). Agricultural development and global trade of food commodities can further cause groundwater depletion in water stressed areas (Duarte et al., 2016). Many studies have demonstrated that massive amounts of water are embedded in food and crops which is circulating around the world through international trade of agricultural commodities (Fracasso et al., 2016). Vallino et al. (2021) and Rosa et al. (2019) have shown how significant quantities of water are moving from one part of the world to another, in patterns unrelated to physical boundaries, or the scarcity and abundance of water. Many countries, especially less developed countries, are net exporters of water even though they are water scarce countries, whilst net importers of water are often not suffering water scarcity (Vallino et al., 2021). This trade in embedded water, called virtual water trade, in the long term is likely to have major consequences on the ecosystems and food security of water scarce countries (Antonelli and Sartori, 2015; Reimer, 2012). Groundwater is a major part of the water used for agriculture and its rate of depletion is alarming in many countries as levels of abstraction are above the rate of recharge of aquifers and groundwater bodies (Jägermeyr et al., 2017). Globally, it is considered that unsustainably used water accounts for about 11% to 15% of the total embedded water associated with international crop trade (Dalin et al., 2017; Rosa et al., 2019).

Global agricultural trade and export specialization has transformed the geography and the economy of many low-middle income countries, which have become major players within global food value chains. One of these is Peru, which is now a global leader in the export of water-intensive crops such as asparagus and grapes, at the expense of scarce water resources and with a heavy reliance on groundwater (Salmoral et al., 2020). Whilst this agro-export boom has supported employment, rural development and economic growth for some people, significant social and environmental challenges for others limit its sustainability. In particular, heavy abstraction for

irrigation is likely to increase pressure on groundwater reserves, particularly given the ever increasing demand for water intensive export crops (Schwarz and Mathijs, 2017). One of the areas where these conflicts are starting to manifest is the Ica Valley in Peru, which after liberalisation of the agricultural land market has seen large agricultural corporations focused on international crop production (mainly asparagus, grapes, onions and avocados) acquiring large areas of land from smallholders (Williams and Murray, 2019). These corporations have developed large areas of intensive irrigation leading to prolonged water crisis for other stakeholders (Muñoz, 2016; Schwarz and Mathijs, 2017; Williams and Murray, 2019). Whilst drip irrigation systems have been deployed to increase productivity, the high value of the crops produced has led to a ‘rebound effect’ (Berkhout et al., 2000; Sorrell and Dimitropoulos, 2008) since the water savings obtained have encouraged expansion of the irrigated area for high value crops, such as asparagus and grapes, increasing the overall withdraw of groundwater rather than conservation of the water resource itself (Berbel et al., 2015; Berbel and Mateos, 2014).

The study of Salmoral et al. (2020) evidenced the groundwater sustainability problem in the Ica Valley related to agricultural intensification highlighting important pressures on water resources in the region. This is a challenge affecting many countries in Latin America and not just Peru and the Ica valley. Based on the findings from Salmoral et al. (2020), we aim to examine what factors are driving the unsustainable use of groundwater in the Ica Valley and what implications this has for sustainable development in the area by applying an econometric approach. We focus on three key drivers: i) the expansion of drip irrigation, ii) the specialization in exporting crop commodities; and iii) the concentration of land by big exporting farms. The findings from this work help to understand the factors promoting unsustainable agricultural expansion in developing countries.

The paper is structured as follows: Section 2 (Background) introduces concepts and background relating to land concentration, crop exports, and water, and describe the case study area, Section 3 (Method) describes sources of data and the empirical strategy employed, Section 4 (Results) shows the main results of the analysis which are commented and discussed in Section 5 (Discussion), the paper ends with some concluding remarks in Section 6 (Concluding Remarks).

2. Background

2.1 Land concentration, exporting food commodities and rebound effects

Foreign Direct Investments (FDI) is a significant global driving force in the agri-food sector and an important booster of local development in low and middle-income countries. FDI in agribusiness has steadily increased in recent decades, peaking during the food price crisis of 2007-2008, in which large international financial speculation was attracted to the agri-food sector by large increases in the rate of return of agricultural assets (Punthakey, 2020; Wegenast et al., 2022). Latin America has also experienced large in-flows of FDI in the agri-food sector in recent decades with a significant proportion of transnational investments from multi-national corporations (Saravia-Matus et al., 2018). On average between 2012 and 2017, Latin America received 13 billion dollars a year in FDI (equal to the 7.9% of the total FDI in the continent) for agricultural investments principally from Western countries (ECLAC, 2019; Mahmood, 2023).

After the food crisis of 2007 land acquisition as a new form FDI in the international arena has become increasingly prevalent (Borras et al., 2012b; Sändig, 2021). During recent decades, global food, energy, finance, and environmental crises, have resulted in farmland becoming increasingly attractive as financial assets, prompting large-scale land acquisition especially in Africa, Asia, and Latin America (Dell'Angelo et al., 2017; Sosa Varrotti and Gras, 2021). There have been wide ranging and contrasting opinions among commentators, academics, and civil society as to the benefits of this process to domestic social, economic and environmental systems (Cotula, 2012; Dell'Angelo et al., 2021; Wegenast et al., 2022).

High global population growth, increased affluence, and the urbanization of middle-income countries, has driven major shifts in diets (e.g. China and India) and the acquisition of agricultural land in emerging and low-income countries, due to the potential profits that can be generated from such investments. In addition, declining productivity and rising agricultural production costs in rich countries (e.g. South Korea, Gulf Countries) and the growing interests in biofuel crops as an alternative form of energy has further stimulated the acquisition of such farmland as an investment option (Cotula, 2012; Deininger and Byerlee, 2011).

These new investment opportunities in the agribusiness sector have attracted financial investment companies, private companies, and public-private partnerships, which unlike agribusiness and energy companies, are not interested in direct production, but in increasing returns and risk management through financial portfolios diversification (Borras et al., 2012b, 2020; Cotula, 2012).

This phenomenon has taken on significant proportions globally, and in 2020, amounted to 33 million hectares acquired through 1865 transactions (Cotula, 2012; Lay et al., 2021). This process is set to grow in the near future, as food and energy crop prices (e.g. biofuel, biodiesel) are expected to rise, exacerbating pressure on land for food production, and increasing the economic attractiveness of agricultural land as an asset (Cotula, 2012; Das and Gundimeda, 2022; Deininger and Byerlee, 2011; Mechiche-Alami et al., 2021).

The acquisition of land manifests itself in different ways, such as long-term licenses or leases, direct sales or through the contracting of national farms. But the key aspect is these actions are devised to gain control of land resources in order to control land use (Borras et al., 2012b).

This process has been termed 'land grabbing', i.e. the acquisition of agricultural land in developing and emerging countries by foreign actors, mainly from richer countries. The definition of land grabbing provided by Borras et al. (2012a) describes a process that is essentially extractive¹, in which the control of land and its resources is ceded to external, international agents (Borras et al. 2012b). This form of control can also be exerted on water resources and some authors have extended the concept of land grabbing to water by using the term 'water grabbing' as a process in which powerful actors capture decision-making rights over water, and then ignore the hydrological complexity of water systems to the detriment of local populations and ecosystems (Chiarelli et al., 2022; Dell'Angelo et al., 2018; Franco et al., 2014, 2013; Mehta et al., 2012; Raimondi and Scoppola, 2022; Woodhouse, 2012).

The appropriation of local water resources, and the effects that this has on local ecosystems and the local economy, can be studied using the 'Virtual Water' concept (Franco et al., 2013). 'Virtual Water' is defined as the volume of water used in food production (e.g. crops, meat) that is then traded on international markets and can be viewed as the water embedded in a food commodity that is exported from one country and imported to another (Hoekstra and Mekonnen, 2012; Vallino et al., 2021).

The virtual trade in water of exporting countries can increase due to both more intensive agricultural uses of land and the expansion of harvested areas for internationally traded crops. Furthermore, an additional effect of large-scale land acquisitions (LSLA) is an increase in rivalry

¹ They define land grabbing as “*the capturing of control of relatively vast tracts of land and other natural resources through a variety of mechanisms and forms that involve large-scale capital that often shifts resource use orientation into extractive character...*” (Borras et al., 2012a).

over scarce water resources amongst local farmers themselves, since the water available for local farms decreases when agribusiness investors with high levels of economic power developing large areas of irrigation infrastructure start to compete with local farmers for water resources (Chiarelli et al., 2022). This can then lead to the displacement of local farmers, who are no longer able to extract water for their own use (Raimondi and Scoppola, 2022).

The introduction of new technological solutions to increase irrigation efficiency in water scarce areas can have significant and unintended consequences in the long term. Pérez-Blanco et al. (2021), through an extensive literature review, showed that the overall economic gains achieved through increased irrigation efficiency did not compensate for the associated and negative socio-economic and environmental impacts. In fact, in the absence of policy instruments, water efficiency intensification often led to an increase in the total water consumption at basin level. The increase in local agricultural income and (occasional) reductions in individual water withdrawals, did not compensate for the costs of reduced downstream water availability, groundwater depletion, and additional investment costs experience by other farmers (Pérez-Blanco et al., 2021).

This is the ‘paradox of irrigation efficiency’ described by Grafton et al. (2018) which is a specific case of Jevon’s paradox (Jevons, 1865). Jevon's theory is widely used in energy economics to describe the 'rebound effects' of increased efficiency in energy use (Khazzoom, 1987; Saunders, 1992). In energy economics, a ‘rebound effect’ occurs when changes in energy technology increase energy productivity and decrease the marginal price paid per unit of energy consumed, resulting in an increase in overall energy demand². If the increase in total demand is greater than the total savings achieved thorough efficiency gains, the so-called ‘rebound effect’ has occurred (Alcott, 2005; Font Vivanco et al., 2016; Polimeni and Polimeni, 2006; Sorrell, 2009).

Several empirical studies have confirmed the existence of ‘water rebound effects’ when total water demand has been increased with the deployment of improved irrigation technologies such as precision drip technologies providing improvements in irrigation efficiency (Espinosa-Tasón et al., 2020; Grogan et al., 2017; Sears et al., 2018; Song et al., 2018; Wang et al., 2020; Ward and Pulido-Velazquez, 2008). The main effect of using drip irrigation is the increase in profits per unit of water used, due to higher production per unit of water used. This has led to a shift to higher

² Following Alcott (2005) an example of the rebound effect is the driver who changes car for a more fuel-efficient model, but consumes more total fuel because of the relative advantage gained from the lower marginal cost of energy, which incentivizes him/her to drive more and for longer distances.

value crops (intensive margin) that may have higher water requirements (Berbel and Mateos, 2014) and incentivised the extension of cultivation to more marginal areas (extensive margin) that were unprofitable before the introduction of the more efficient irrigation systems. These two processes have increased the overall consumption of water for irrigation, increasing pressures on water resources (Caswell, 1989). These effects can negate water conservation policies and demonstrate that agricultural production is ultimately constrained by the natural resource base despite gains in technological efficiency.

2.2 The case study area

Land grabbing in Latin America has resulted in large areas of land becoming concentrated and controlled by external interests³ (Borras et al., 2012b, 2012a). In Peru, land concentration by both western and Latin American corporations (i.e. from Colombia and Chile) with an interest in high value products such as fruits and vegetables, has greatly increased in the last three decades, (Gomez, 2014; Soto Baquero and Gómez, 2013). These new agro-exporting companies have introduced advanced technologies for irrigation (Gomez, 2014) and the areas where corporations have concentrated their control of land has been strongly linked to areas where water accumulates in large quantities (Damonte and Boelens, 2019). These processes have been particularly evident in one of the most productive area of Peru, the Ica Valley, whose aquifer contains almost one third of the country's groundwater resources (Boelens et al., 2014; Franco et al., 2014).

The Ica Valley is located 300 km south of Lima, the capital of Peru. The valley is one of the most productive areas on the Peruvian coast, and is an early and important player in the agro-export boom that has taken place since 2000 (Damonte and Boelens, 2019; Zegarra, 2018). A particular feature of the valley is that about 70 to 80% of the water used for export agriculture is extracted from the Ica-Villacurí aquifer (Peña et al., 2010). During the last 30 years, 63% of the land in the valley has transitioned from traditional production to export-led production (Zegarra, 2018). This type of change has also occurred in other parts of the Peruvian Coast, specifically in the north in *La Libertad* and *Piura regions* (Zegarra, 2019). In these two cases, however, the agricultural sector is not as dependent on groundwater resources as in the Ica Valley, and this reduced the negative

³ Although land grabbing in Latin America has been marked, as in sub-Saharan Africa, only by Brazil and Argentina, throughout the continent there has been an important process of land concentration and 'foreignisation' of land (Gomez, 2014).

impacts of LSLA on water resources in the two regions, as irrigation activities could also rely on a good availability of surface water resources.

The use of groundwater gives exporting farms the key advantage of being able to export at almost any time of the year, and supply the market when there is lower competition from other more seasonal areas of production. It also gives these firms good quality water, needed for the production of high value fruits and vegetables. At the same time, this high dependency on groundwater is problematic for the valley, as there is mounting evidence of the aquifer is being seriously depleted (ANA, 2016; Cárdenas, 2012; Damonte and Boelens, 2019; Oré et al., 2011). This means an uncertain future for the export sector as well as all the other 300,000 water users in the Province of Ica (Cancino, 2012; Muñoz and Zúñiga, 2018).

The growth of export crops from the Ica Valley is shown in Figure 1. From 2000 to 2019, mean annual growth was approximately 14.3%, and the exported value in 2019 was 16 times that of 2000. The main exported crops are grapes and asparagus, but also to a lesser degree, avocados, onions, tangerines and recently, blueberries⁴. In the same graph we depict three projected scenarios. These scenarios are generated as hypothetical future scenarios and are not based on any predictive modelling. We assume linear, quadratic and cubic specifications for the time variable in each scenario (Zegarra, 2019). In the inertial linear projection, where growth continues to increase at the same rate as observed for the last two decades, exports increase from US\$ 650 million in 2019 to US\$ 985 in 2030, a 50% increase. In the more expansive quadratic scenario, exports will reach about US\$ 1,450 in 2030, more than double the value of 2019 exports. Finally, in the low growth cubic scenario, exports will only increase to US\$ 750 in 2030, up by 15% on 2019 exports. These possible scenarios are proposed here as there is heated debate in Peru about the feasibility of any of them in terms water sustainability. In particular, the linear and quadratic growth rates, which will require even more intensive water exploitation of the already stressed Ica-Villacurí aquifer, raise major concerns when considering export-led agricultural intensification and the availability of natural resources to support such growth in the future.

⁴ Most of the exported food commodities from the Ica Valley are traded by large companies responsible of LSLA.

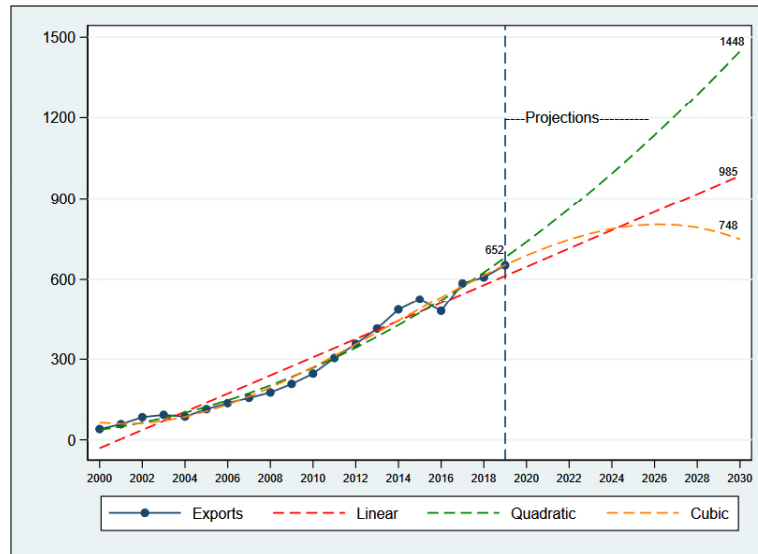


Figure 1. Exports from the Ica Valley (US\$ Million). This shows the growth of total exports between 2000-2019 in US\$ millions and includes three hypothetical projections for 2020-2030 based on linear, quadratic and cubic specifications as potential scenarios.

The agriculture of the Ica valley is heavily dependent on the Ica-Villacurí aquifer because the Ica river, that flows through the valley, is fed by rainwater in the highlands and is seasonal, with six months of the year where almost no water flows at all. Surface water irrigation is therefore mostly practiced by small farms using traditional irrigation techniques with low value crops that are sold in local and regional markets. In contrast, large farms use the bulk of groundwater extracted from the Ica-Villacurí aquifer for export crops, using advanced drip irrigation technologies and modern packing plants located in the Ica Valley.

The process of agro-export expansion has concentrated land and water resources in the valley into fewer farms. Using agricultural census data, we estimated that the Gini coefficient⁵ for land distribution changed from 0.79 in 1994 to 0.86 in 2012. Bauluz et al. (2020) estimated a Gini coefficient of 0.92 for agricultural land in Peru using the Agricultural Census of 2012. Although the Ica Valley had a smaller coefficient (0.86) than the national figure in 2012, it still increased from a value of 0.79 between 1994-2012. This suggests that in the Ica Valley, there has been a significant process of land concentration which has created greater inequality in the distribution of land between large and small farms. In the case of water rights, data taken from the National Water

⁵ The Gini coefficient measures the inequality among the values of a frequency distribution, such as levels of income. A Gini coefficient of 0 reflects perfect equality, where all income or wealth values are the same, while a Gini coefficient of 1 (or 100%) reflects maximal inequality among values, a situation where a single individual has all the income whilst all others have none.

Authority (ANA) gave us an increase in the Gini coefficient from 0.61 in 1998-2005 to 0.90 in 2006-2017, showing that access to water has also been concentrated in larger farms. In addition, larger exporting farms (defined as having more than US\$ 10 million in annual sales) have been growing at a much faster rate than smaller exporting farms since 2012 (see Figure 2).

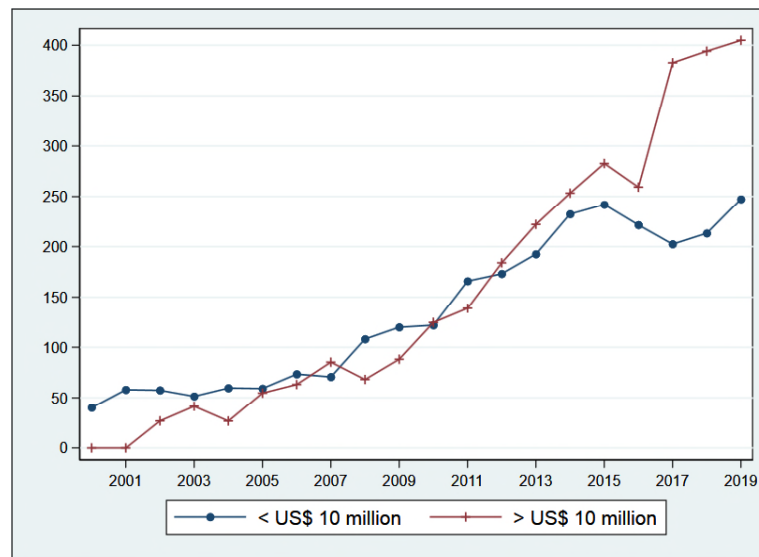


Figure 2. Annual export value from the Ica Valley (US\$ Millions). This shows the annual growth in crop value exported from 2000 to 2019 classifying exporters into two groups: (i) large exporters (more than US\$ 10 million in annual revenue in 2019); (ii) small-medium exporters (less than or equal to US\$ 10 million in annual revenues in 2019).

The Ica valley shows a clear process of specialization and land concentration, as can be seen in Figure 3. In Map 1.a. we can see the importance of drip irrigation in the valley, showing the predominance of drip irrigation technology in the Villacuri area (upper north), and large areas in the middle and lower areas of the valley. In Map 1.b. we can see also the high level of crop specialization in two main products: asparagus and grapes, which are the main exported crops. In Map 1.c. the degree of land concentration is shown, which is especially high in areas with high levels of drip irrigation and crop specialization.

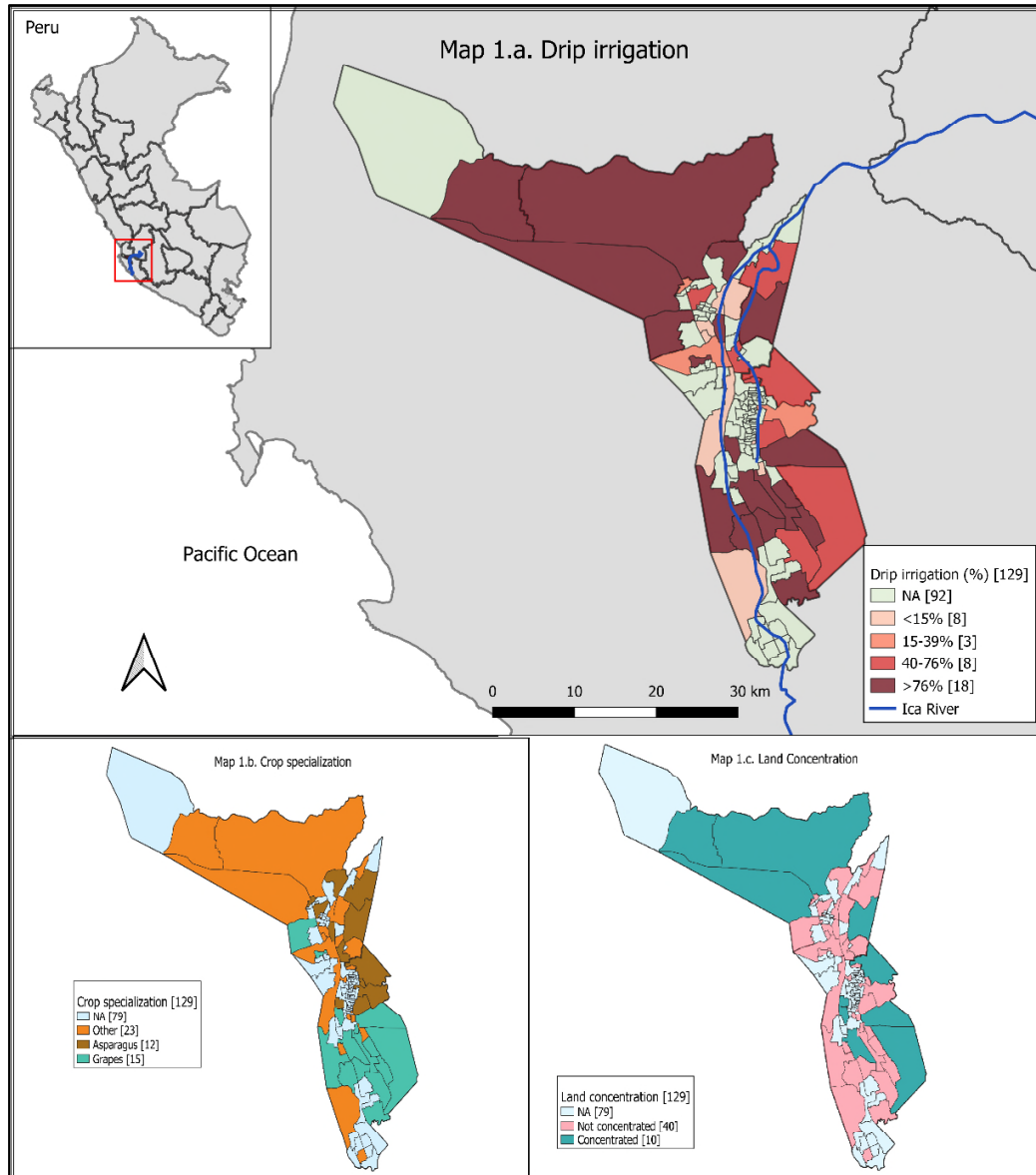


Figure 3. Map 1.a. Percentage of land with drip irrigation on total agricultural land at tract level in the Ica Valley. Map 1.b. Crop specialization in asparagus, grapes or others (avocados, onions or pecan nuts) in the Ica Valley. A tract is considered to be specialized in a particular crop if more than 40% of the agricultural area is in that crop. Map 1.c. Land concentration in the Ica Valley based on the percentage of large farmers in the track. Tracks with more than 60% of large farmers owning more than 50 Ha are considered to be “concentrated”.

3. Method

3.1 The Groundwater sustainability index

This study builds on work by Salmoral et al. (2020), extending the analysis to include socio-economic drivers of water use in the Ica Valley. The study by Salmoral et al. (2020) was an analysis of the trade-offs between irrigation needs and aquifer recharge potential across different crop mixes and farming systems in the Ica Valley. It assessed how the impact of an expansion in irrigated agriculture resulting from LSLA by large farms involved in the international trade of food commodities could affect water availability and sustainability. It used a number of approaches, applying different tools and indicators to predict water extraction (e.g. the WaSim model, water footprint, water productivity and water sustainability use indices) and undertook a multi-criteria assessment of blue water consumption and related economic benefits on the long-term sustainability of water resources for different crops and farm types (i.e., small vs large farms) for different geographical zones of the valley.

In this study, we focused on the determinants of groundwater extraction using one indicator developed by Salmoral et al., (2020) for the blue water sustainability index (BIWSI) (see also Wada et al., 2014) and combine this with econometric modelling to consider the effects of census tract⁶ drip irrigation intensity, export crop specialization, and the concentration of land in large farms on groundwater renewal and aquifer replenishment.

We took the results from the study by Salmoral et al. (2020) to assess how different factors are leading to unsustainable water use in the Ica valley. We used data from Salmoral et al. (2020) who calculated the BIWSI, using data from the National Water Authority (Autoridad Nacional del Agua in Spanish) (ANA, 2017) and modelled data on irrigation demand from a water balance model called WaSim (Hess et al., 2000), for the eight different geographical areas in the Ica Valley between 2015 to 2018. More specifically, we used a modified version of BIWSI for groundwater that we called groundwater sustainability index (GWSI). The index ranges from 0 (totally

⁶ The agricultural census of 2012 divided agricultural land into so called census tracts, which are territorial units which have approximately 100 farms per tract. These units are used for operational purposes during the census process. We have kept the original tracts which totally overlap with the Ica Valley, and cut the areas which are not part of agricultural land in the valley. The Ica Valley has 129 census tracts as shown in Figure 3.

unsustainable) to 1 (sustainable)⁷ and identifies the proportion of unsustainable water use that takes place in a specific area. It represents the proportion of net groundwater that was used for agricultural productions without replenishment over the total water used and it has been calculated simply rescaling the BIWSI indicator of Salmoral et al. (2020) in an increasing scale.

The spatial level of analysis was the census tract level from the Province of Ica's 14 municipalities. Thus, for each spatial area i (defined as census tract), the GWSI is given by Equation 1 as:

$$GWSI_{i,t} = 1 - \frac{WF_{blue,GW_{i,t}} - GWR_{i,t}}{WF_{blue,GW_{i,t}}} \quad \text{eq.1}$$

Where: $WF_{blue,GW_{i,t}}$ is the blue water footprint (in m^3) as defined by Mekonnen and Hoekstra (2011) and is a proxy for the absorption of groundwater in area i at time t in m^3 ; $GWR_{i,t}$ is the natural replenishment of groundwater in census tract i at time t in m^3 . Groundwater recharge data were obtained from the National Water Authority (ANA, 2017), which included the recharge from the Ica River and tributaries, water channels, and irrigation water return flows⁸.

The numerator of the index thus represents the non-renewable groundwater abstraction level in m^3 , whereas the denominator indicates the total level of groundwater used for irrigation. The index therefore shows the ratio between the level of groundwater used for irrigation that is not covered by natural water recharge, and the total groundwater used for irrigation for each area i considered in the model. Thus, the GWSI shows the proportion of net groundwater that has been used without replenishment as a function of the total water used in the area.

The spatial distribution of the GWSI in the Ica Valley is shown in Figure 4.

⁷ We adapted the calculation made in Salmoral et al. (2020) to suit our econometric model. We used $1 - BIWSI_{i,t}$ from Salmoral et al. (2020) to scale from 0 to 1 to make BIWSI more intuitive for econometric applications. In Salmoral et al. (2020), 0 was considered to be sustainable whilst 1 was considered to be fully unsustainable.

⁸ The sum of the recharge from the river, tributaries and water channels was divided by the whole Ica-Villacuri aquifer area (127,440 ha) to derive an annual water recharge per unit area (i.e., 142 mm). The recharge from irrigation was estimated by dividing the actual evapotranspiration (ETa) by the irrigation depth obtained from the WaSim model assuming a water application efficiency of 60% for surface irrigation and 100% for drip irrigation (i.e., with surface irrigation only the 60% percentage of the water applied is consumed by the crops while 40% is released in the water basin, while for drip irrigation it was assumed that all the water applied was consumed by the crops and 0% of water is released into the water basin). The estimated recharge per unit area in the aquifer was later multiplied by the area of the aquifer within each zone in order to estimate volumetric recharge (Salmoral et al., 2020).

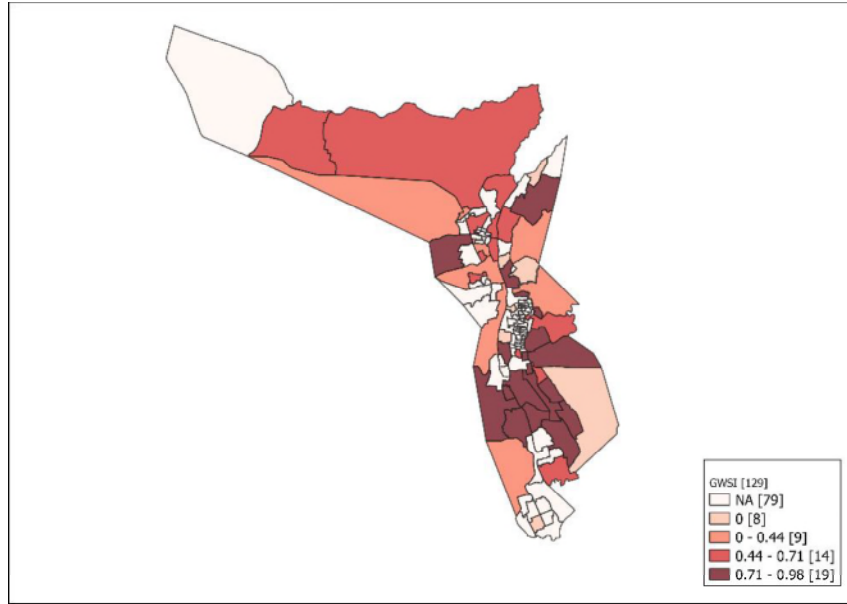


Figure 4. GWSI for the Ica Valley. This shows the estimated value of GWSI based on the average for 2015-2018 period.

3.2 Factors influencing sustainability

For our analysis we used data from the National Agriculture Survey (ENA, 2022), a socio-economic survey undertaken at national level. We used the data from ENA for the Ica valley from 2015 to 2018 which described agricultural cropping patterns, economic benefits, and water resource use at the farm level. We aggregated the data to census tract level, the lowest geographical level at which the data for BIWSI and WD was calculated in Salmoral et al. (2020). Our unit of observation was the census tract level, and all the data were aggregated using mean values at tract level in the dataset obtaining an unbalanced panel of 130 observations (2015 to 2018).

To answer our research questions, we focused on three key aspects of water use in the Ica valley using the following proxy variables to indicate sustainability.

1. The rebound effect on water resources due to the expansion of more efficient irrigation technologies for crop production. We measured this by calculating the annual ratio of drip irrigation over the total irrigation per census tract in each year.
2. The specialization of each census tract in exporting crop commodities. We identified this by determining whether the cultivation of export-oriented crops (avocados,

asparagus, grapes, onions or pecan nuts) in the tract was greater than 70%⁹ of the total cropped area of the tract in each year. We further analyzed the effect of specialization in asparagus and grapes.

3. Land concentration in large farms. We measured the proportion of large farms in each tract by taking the ratio of the cropped area of large farms to the total cropped land of the tract in each year as an indicator of land concentration by large farms.

3.3 Control variables

To control for other influencing factors of groundwater sustainability we considered different climatic factors. We focused on the effect of rain and temperature on water demand and groundwater availability using climatic data from four weather stations interpolated for each tract¹⁰ and taken as the average over the period from 1966-2013. This was then used as a proxy of the climatic conditions in the tract. This is important as the Ica valley has some heterogeneities in climatic conditions particularly between the coast and internal areas. We considered the seasonality of the climatic variables as the area is characterized by a wet season from May to September with lower temperatures and higher levels of water availability from greater precipitation and glacier melt, and a dry season from October to April in which average temperatures are higher and precipitation is erratic (Salmoral et al., 2020). Specifically, we considered:

- the average seasonal accumulated precipitation in each tract from 1966-2013 both in the dry and wet season, as precipitation patterns can strongly influence both water withdrawal and aquifer replenishment.
- the average of the difference between the maximum and minimum temperature for each tract from 1966-2013 since the differences in temperature conditions can alter the productivity and quality of crops.

⁹ The exporting crops specialization has been considered for each crop individually. Thus, the dummy variables indicating the specialization of the tract had a value of 1 if at least the 70% of the total cultivated area of the census tract was devoted to the production of one of the following crops: avocados, asparagus, grapes, onions, or pecan nuts. Groups of crops had not been considered (e.g., avocados and onions together).

¹⁰ The weather stations are: 1) Hacienda Bernales; 2) Huamani; 3) San Camilo; 4) Ocucaje. Spatial interpolation: with the mean values per station we interpolated (raster) the climate data for all the tracts in the Ica Valley (mean of raster values per tract).

In addition, we controlled specific socio-economic factors which can affect the level of groundwater sustainability. We used census data¹¹ aggregated to tract level to identify the average educational level of the head of the farm (number of years in schooling) and the average age of farmers as main socio-economic and demographic characteristic in each tract. These have been shown to influence water conservation behavior and irrigation technology adoption in past studies (Alcon et al., 2019; Moreno and Sunding, 2005; Pokhrel et al., 2018; Skaggs, 2001). We also controlled for the degree of agricultural specialization of the tract by considering the proportion of agricultural land use of each tract in terms of intensity of agricultural activity in each tract given by the total cropped area (in logarithm form for smoothing the distribution) in each year using data from the National Agriculture Survey (ENA).

3.4 Groundwater sustainability index modelling framework

We used an econometric approach to examine the effect of different explanatory variables on the groundwater sustainability index defined in the previous section. This used various model specifications to consider the different factors influencing the sustainability of groundwater in the Ica Valley.

Initial results showed that there was a high pair wise correlation between our major explanatory variable of interest: micro-irrigation intensity, crop specialization and land concentration (see Appendix). We therefore considered these variables in separate models to preserve the individual information of those factors on sustainability in the area of study. Our dependent variable GWSI, the groundwater sustainability indicator, is in fractional form and bounded between 0 and 1 which imply that we cannot rely on traditional OLS approaches as it is not suitable for this type of data leading to inconsistent results (Wooldridge, 2010). We used a double empirical strategy to cope with the distribution of our dependent variable using a two-limit Tobit model to consider the distribution concentrations at 0 and 1, which are common to corner solution variables as in our case¹² (Wooldridge, 2010). We added a fractional model for robustness checking as in the work of Arslan et al. (2014). For the fractional model we used the pooled Quasi Maximum Likelihood

¹¹ Census data were available only for the year 2012. These gave us an idea of the main socio-economic heterogeneities among geographical tracts within Ica Valley.

¹² A corner solution outcome can be considered a non-negative variable with a continuous distribution over strictly positive values. It can be applied to fractional outcomes in which is easy to get pile-ups in 0 and 1 points, with continuous values between the two values (See Appendix). The main difference between censored and corner solutions is that we observe the entire possible range of outcome of the variable (Wooldridge, 2010).

Estimation (QMLE) of Papke and Wooldridge (2008, 1996). In addition, we controlled for unobserved heterogeneity using a correlated random effect model as in Wooldridge (2019, 2010), Shunck (2013), Arslan et al. (2014) and Auci and Vignani (2021). Our baseline model is shown in Equation 2:

$$y_{i,t}^* = \sum_1^M x_m \beta_{m,i,t} + u_i; u_i | \sim N(0, \sigma^2) \quad \text{Eq. 2}$$

$$\begin{cases} y = 0 \text{ if } y^* \leq 0 \\ y = y^* \text{ if } 0 < y^* < 1 \\ y = 1 \text{ if } y^* \geq 1 \end{cases}$$

Where: y is the latent fractional variable which have two accumulation points at 0 and 1; $y_{i,t}^*$ is the outcome of the observed variable between 0 and 1 which have a continuous distribution; x_m are the M covariates included in the model with a constant term as first element; $\beta_{m,i,t}$ are the M estimators of the coefficient for each tract i and year t ; u_i is the idiosyncratic error uncorrelated with the regressors and normally distributed with 0 mean and σ^2 variance.

Due to the small sample and also data that showed low variation in time (both the climatic and demographic variables were quite stable) we were not able to apply a fixed-effect model to reduce bias in the estimations from unobserved heterogeneity. Therefore, we extended our baseline model employing the Mundlak device (1978) and adopted a Correlated Random Effect approach (CRE) (Papke and Wooldridge, 2008; Wooldridge, 2010). The CRE approach considers that the error term is composed of two main terms: an unobserved individual part which can be partially correlated with the regressors using a specific structure and an idiosyncratic part that is not correlated with the regressors and is completely random (Wooldridge, 2019) as in Equation 3.

$$u_i = v_i + a_i \text{ with } v_i | X_i \sim N(\psi + \bar{X}_i \xi, \sigma_a^2) \quad \text{Eq.3}$$

By using the CRE approach we can relax the assumption of total independence between the covariates and the error term of the random effect models. The CRE econometric approach assumes that the individual error component is correlated with the time-mean of the time-variant (not applied to constant terms) regressors $\bar{X}_i \xi$ with $\bar{X}_i = T^{-1} \sum_{t=1}^T X_i$ and being σ_a^2 the constant variance of the idiosyncratic part a of the error term u_i (Arslan et al., 2014; Wooldridge, 2019) as

in Equation 2. This reduces endogeneity bias providing robust and consistent estimation of the regression coefficient and allowing for the use of time non-varying variables which are omitted with the use of fixed effects models (Auci and Vignani, 2021; Schunck, 2013). By adding Equation 3 to Equation 2 we obtain our main model in Equation 4, the two-limit CRE Tobit.

$$y_{i,t}^* = \sum_m^M x_m \beta_{m,i,t} + \psi + \sum_n^N \bar{X}_i \xi_n + a_i; a_i | X_i \sim N(0, \sigma_a^2) \quad \text{Eq.4}$$

This equates to Equation 3 but includes the addition of the time mean regressors of the non-constant variables (percentage of micro irrigation, crop specialization, cropped area and land concentration). When considering the fractional nature of the dependent variable by employing the fractional probit our model takes the form showed in Equation 5.

$$E(y_{i,t} | x_{i,t}, c_i) = \Phi(x_{i,t} \beta_a + c_i) \quad \text{Eq.5}$$

where: the conditional expectation on y is in an index form; Φ is the standard normal cumulative distribution function (cdf) which is strictly monotonic allowing for the computation of the average partial effects; $x_{i,t}$ as before are the regressors and here strictly exogenous, β_a are the estimated coefficients and v_i is the unobserved effect which appears additionally into standard cdf. As for the tobit model, we used the CRE approach to deal with unobserved heterogeneity by assuming possible correlation between some part of the unobserved individual error c_i and the covariates as in Eq. 6. This was inserted into Eq.7 as part of the main fractional probit model as in Papke and Wooldridge (2008) and Arslan et al. (2014).

$$c_i | (x_{i1}, x_{i2}, \dots, x_{iT}) \sim N(\psi + \bar{X}_i \xi, \sigma_a^2) \quad \text{Eq.6}$$

$$E(y_{i,t} | x_{i,t}, a_i) = \Phi(\psi + x_{i,t} \beta + \bar{X}_i \xi + a_i) \quad \text{Eq.7}$$

Our model in a fully specified form is presented in Eq. 8 where it incorporates drip irrigation, specialization in exporting crops, and agricultural intensity, and Eq. 9 where it includes only large

farm land concentration. These specifications are valid and used both for the two-limit CRE tobit and the fractional probit model¹³.

$$\begin{aligned}
GWSI_{i,t} = & \beta_0 + \beta_1 Drip_{i,t} + \beta_2 Specialized_{i,t} + \beta_3 Ln\ Cropped\ Area_i + \beta_4 Age_i \\
& + \beta_5 Education_i + \beta_6 Precipitation1_i + \beta_7 Precipitation1_i \\
& + \beta_8 Temperature\ range_i + \beta_9 \overline{Drip_t} + \beta_{10} \overline{Specialized_t} \\
& + \beta_{11} \overline{Ln\ Cropped\ Area_t} + a_t + u_{i,t}
\end{aligned}$$

Eq.8

$$\begin{aligned}
GWSI_{i,t} = & \beta_0 + \beta_1 Large\ farmers_{i,t} + \beta_2 Age_i + \beta_5 Education_i + \beta_6 Precipitation1_i + \\
& \beta_7 Precipitation1_i + \beta_8 Temperature\ range_i + \beta_9 \overline{Large\ farmers_t} + a_t + u_{i,t}
\end{aligned}$$

Eq.9

Where: *Drip* is the ratio of drip irrigation over the total irrigation in the i_{th} tract in year t , *Specialized* is a dummy equal to 1 if the land of exporting commodities >70% cropped area in i_{th} tract in year t , *Ln Cropped area* (in hectares) is the logarithm of the total cropped area in the i_{th} tract in year t , *Age* is the average age (in years) of the farm head in 2012 in the i_{th} tract, *Education* is the average years of schooling (in years) in 2012 in the i_{th} tract, *Precipitation 1* is the average accumulated precipitation (in mm) from 1960 to 2014 in the dry season (from October to April) in the i_{th} tract; *Precipitation 2* is the average accumulated precipitation (in mm) from 1960 to 2014 in the humid season (from May to September) in the i_{th} tract; *Temperature range* is the average difference between maximum and minimum temperature (°C) from 1960 to 2014 in the i_{th} tract and a_t is a year dummy. We also extended Eq. 8 using *Specialization* split into other two dummy variables (Asparagus and Grapes) which was equal to 1 if the land cultivated under asparagus and grapes was more than 70% of the cropped area in the i_{th} tract in year t . Eq.9 differs from Eq.8 but only due to the inclusion of the variable *Large farmers* which is the percentage of cropped land used by large farmers over the total cropped area in i_{th} tract in year t , whereas at the same time *Drip* and *Specialized* have been excluded in the model.

¹³ The only difference between the CRE model and the fractional probit model is that the latter do not consider time as in a panel data form, but it works in cross-sectional framework. Therefore, our dependent variables $GWSI_i$ and for all the covariates the subscript t is not used.

4. Results

4.1 GWSI results

The results for GWSI are shown in Table 1 and 2, where Table 1 shows the results for all crops, and Table 2 for grapes and asparagus only. The coefficient of the tobit model can be interpreted directly as the marginal effects of an additional unit of the independent variable on the dependent variable (columns 1 and 4 in Table 1 and 2). Whereas to consider the marginal effects of the fractional model, being non-linear, we should use the average partial effects that are given in the form of elasticities (column 3 and 6 in Table 1 and 2), therefore they can be interpreted as the change in percentage of the dependent variable due to a 1% change in the independent variable.

In most of the models we found GWSI to be associated with drip irrigation intensity and export crop specialization (columns 1 to 3), as well as large farm land concentration (columns 4 to 6).

In the first specification (columns 1 to 3, Table 1) using all export crops to identify the specialization level of the tract, we found a negative effect of export specialization on GWSI of -0.1 with both the tobit and the fraction model (column 3 for the marginal effects, Table 1). Using the fractional model the drip irrigation intensity was found to be statistically significant with a negative effect of -0.12 on GWSI, whereas the drip irrigation ratio did not show any statistical significance using the tobit model. In the second specification (columns 4 and 6 in Table 1) for large farm concentration we found a negative impact on GWSI of -0.36 and -0.3 respectively using tobit and the fractional model. A similar pattern seems to exist in Table 2 when considering export crop specialization to include only grapes and asparagus. However, only grape specialization is a relevant factor for a negative impact on GWSI with a coefficient -0.17 only for the tobit model (column 1, Table 2), whereas the estimated coefficient of asparagus specialization is never significant. The effect of the intensity of drip irrigation is confirmed with coefficients of -0.28 for drip only with fractional model (column 3, Table 2). Land concentration of large farms was found statistically significant only for the fractional model with an effect of on GWSI of -0.24 (column 6, Table 2).

An important part of the impact on GWSI is explained by the intensity of cropping (land cropped) in the tract which ranges from -0.1 (column 3 Table 2) to -0.25 (column 1 Table 2). Conversely, a relevant aspect is the average level of education which impacts positively on the GWSI by 0.5 with a strong significance level in the fractional model (column 6 with the specification using large

farm concentration, Table 1). This underlines the important role of education in influencing the sustainable use of natural resources.

These findings highlight that most factors analyzed (apart education) are negatively influencing the sustainable use of groundwater in the Ica valley. An increase in the use of drip irrigation reduces the GWSI on average by between -0.12 and -0.28 points of the indicator for every 1% change in the ratio of drip irrigation over total irrigation, therefore evidence of a rebound effect due to the adoption of more efficient irrigation systems is evident.

As expected, another element impacting the state of groundwater sustainability is the specialization of the tract in the production of agricultural commodities for international trade. In fact, the higher the area used for internationally traded commodity crops, the lower is the level of GWSI. Since the variable used is a dummy (which takes the value 1 if the area cultivated for exporting crops is equal or higher than the 70% of the total cropped area), the effect of being a census tract specialized in exporting crops in comparison to a census tract non-specialized in exporting crop is an average reduction of -0.1 in the GWSI. Therefore, tract specialization in exporting crops grown in the Ica Valley (either grapes, asparagus, avocados, pecan nuts or onions) leads to a reduction in the sustainable use of groundwater resources. Specialization in grape production appears to be main the driver of this effect (a reduction of -0.17 in the GWSI if a census track is specialized in grape cultivation), whereas asparagus is not a statistically significant factor of impact on the sustainability of groundwater resources (column. 1 and 3, Table 2).

Large farm land concentration is strongly linked to export crop specialisation, and this analysis indicates that the concentration of land into large farms has a large negative impact on the GWSI reducing it by between -0.24 and -0.3 for every 1% change in the land concentration (using the fractional model column 6 in Table 1 and 2) and of -0.36 for additional increase in the in the proportion of agricultural land used by large farms (using the tobit model column 4 in Table 1). Climatic variables are never statistically significant as their spatial variability is low.

Table 1. Econometric estimations and marginal effects of drip irrigation, exporting crop specialization (all exporting crops) and large farm concentration on GWSI using Linear, Tobit and Fractional model.

VARIABLES	(1) Model 1 Tobit CRE	(2) Model 2 Fractional CRE	(3) Model 2 Margins	(4) Model 3 Tobit CRE	(5) Model 4 Fractional CRE	(6) Model 4 Margins
Drip irrigation	-0.159 (-1.620)	-0.372** (-1.974)	-0.121** (-1.983)	-	-	-
Specialized	-0.108** (-2.656)	-0.315** (-2.512)	-0.102** (-2.484)	-	-	-
Ln Cropped area (Ha)	-0.244*** (-5.677)	-0.605*** (-5.964)	-0.196*** (-6.288)	-	-	-
Age (years)	-0.0839 (-0.929)	-0.192 (-1.049)	-0.0621 (-1.058)	-0.119 (-1.360)	-0.218 (-1.354)	-0.0779 (-1.387)
Education (years)	-0.0449 (-0.105)	1.060 (1.196)	0.344 (1.181)	0.235 (0.611)	1.417** (2.005)	0.506** (2.073)
Precipitation 1 (mm dry season)	-0.0390 (-0.0968)	-0.0593 (-0.412)	-	-0.0178 (-0.109)	-0.0140 (-0.133)	-
Precipitation 2 (mm in wet season)	-0.0838 (-0.0246)	-0.999 (-0.358)	-	0.509 (0.309)	-0.0506 (-0.0260)	-
Temperature range (max temp – min temp)	-0.194 (-0.219)	-0.297 (-1.140)	-	-0.0806 (-0.246)	-0.0675 (-0.296)	-
% of large farms	-	-	-	-0.366* (-1.970)	-0.849*** (-2.949)	-0.303*** (-3.019)
Constant	9.970 (0.550)	13.93 (0.988)	--	7.681 (0.885)	7.686 (0.665)	-
Observations Number of id_tract Type	130 50 Correlated Random Effect	130 Fractional Probit	130 Fractional Probit	130 50 Correlated Random Effect	130 Fractional Probit	130 Fractional Probit
Robust	Jackknife	Cluster Tract	Cluster Tract	Jackknife	Cluster Tract	Cluster Tract
Individual Fixed eff	Yes CRE	Yes Mundlak	No	Yes CRE	Yes Mundlak	No
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Tract	All	All	All	All	All	All
specialization	Exporting Crops	Exporting Crops	Exporting Crops	Exporting Crops	Exporting Crops	Exporting Crops

Table 2. Econometric estimations and marginal effects of drip irrigation, exporting crop specialization (grapes and asparagus) and large farm concentration on GWSI for Linear, Tobit and Fractional model.

VARIABLES	(1) Model 2 Tobit CRE	(2) Model 3 Fractional CRE	(3) Model 3 Margins	(4) Model 4 Tobit CRE	(5) Model 5 Fractional CRE	(6) Model 5 Margins
Drip irrigation	-0.141 (-1.598)	-0.855** (-1.973)	-0.279* (-1.870)	-	-	-
Specialized (ASPA)	-0.0312 (-0.342)	-0.351 (-1.029)	-0.115 (-1.054)	-0.0175 (-0.206)	-0.0900 (-0.424)	-0.0316 (-0.424)
Specialized (GRAPES)	-0.166*** (-3.266)	-0.190 (-0.749)	-0.0620 (-0.760)	-0.0640 (-0.824)	-0.218 (-1.242)	-0.0765 (-1.235)
Ln Cropped area (Ha)	-0.249*** (-5.860)	-0.317*** (-4.266)	-0.104*** (-4.805)	-	-	-
Age (years)	-0.0829 (-0.943)	-0.200 (-1.230)	-0.0654 (-1.242)	-0.115 (-1.311)	-0.193 (-1.221)	-0.0680 (-1.253)
Education (years)	-0.193 (-0.469)	0.611 (0.936)	0.199 (0.931)	0.0499 (0.131)	1.055 (1.542)	0.371 (1.529)
Precipitation 1 (mm dry season)	-0.0398 (-0.110)	-0.130 (-0.895)	-	-0.0317 (-0.303)	-0.0712 (-0.618)	-
Precipitation 2 (mm wet season)	0.115 (0.0378)	-0.242 (-0.105)	-	0.720 (0.568)	0.272 (0.139)	-
Temperature range (max temp – min temp)	-0.146 (-0.186)	-0.317 (-1.331)	-	-0.0219 (-0.135)	0.0431 (0.251)	-
% of large farms	-	-	-	-0.328 (-1.613)	-0.697** (-2.102)	-0.245** (-2.116)
Constant	9.774 (0.603)	17.25 (1.431)	-	7.408 (1.094)	6.531 (0.590)	-
Observations Number of id_tract	130 50	130	130	130 50	130	130
Type	Correlated Random Effect	Fractional Probit	Fractional Probit	Correlated Random Effect	Fractional Probit	Fractional Probit
Robust	YES Jackknife	YES Cluster Tract	YES Cluster Tract	YES Jackknife	YES Cluster Tract	YES Cluster Tract
Individual Fixed eff	Yes CRE	Yes Mundlak	No	Yes CRE	Yes Mundlak	No
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Tract specialization	Asparagus and Grapes	All Exporting Crops	All Exporting Crops	Asparagus and Grapes	All Exporting Crops	All Exporting Crops

5. Discussion

Our analysis highlighted an inverse relation between groundwater sustainability in terms of water withdrawal (GWSI) in the Ica Valley and the intensity of irrigation (drip technology), commodity specialization and concentration of large farms. These results agree with previous studies on the sustainability issues of agricultural development in the area (Boelens et al., 2014; Chiarelli et al., 2022; Dell'Angelo et al., 2021, 2018, 2017; Franco et al., 2014). The proliferation of large farms focused on the production of agroexport commodities increases the level of groundwater extraction which does not return to the aquifer due to the intensification of drip irrigation. Highly efficient irrigation technologies (drip) produce an intensification and expansion effect on users which causes additional overall demand on natural resource causing a general over-use of water at regional level. This is a clear example of the “rebound effect” due to the commodification of the area, which on one hand is creating job opportunities, local development and economic growth but on the other hand is depleting water resources, so crucial for the local economy.

Land use specialization in export crops is an evident factor influencing unsustainable water use due to a high level of groundwater extraction. The two main agroexport crops cultivated in the area, grapes and asparagus, have affected the sustainability of groundwater resources in different ways. Grapes were shown to have a statistically significant effect with water depletion in terms of GWSI, whereas we did not find any evidence that asparagus specialization in the census tract was correlated with GWSI.

Asparagus and grapes are the two main export crops of the Ica Valley, and together account for 67% of the total blue water footprint, with 92% of the volume extracted from groundwater (Salmoral et al. 2020). The two crops do not differ in terms of irrigation technologies, as both rely on drip irrigation due to their high-water requirements. The main reason for the higher statistical significance of grapes compared to asparagus may be due to the difference in the intrinsic value of the two crops in terms of water units (i.e., market value of the crop sold per each unit of irrigation water used). This confirms that intensification of high-value crops due to LSLA may increase water extraction, thus at the same time decreasing the sustainability in use of water resources (García Morillo et al., 2015).

Indeed, in every area of the Ica Valley, grapes have shown a higher level of productivity than asparagus. Salmoral et al. (2020) defined water productivity as the revenue obtainable in terms

of Soles per m³ of water used to produce a specific crop. Grapes showed productivity values between 4.8 Soles/m³ and 7.6 Soles/m³, while asparagus showed productivity values between 1.4 Soles/m³ and 2.6 Soles/m³.

Another factor influencing the higher explanatory power of grape specialisation compared to that of asparagus could be the fact that grapes are cultivated everywhere in the sub-areas of the Ica Valley, whereas asparagus is only cultivated in a few specific areas. Therefore, the higher number of specialised grape areas may further explain the higher level of statistical significance in influencing the GWSI.

The region under study is the main exporting region of agricultural commodities in Peru and one of the largest exporters in Latin America to western markets (Boelens et al., 2014; Gomez, 2014). However, the Ica Valley, where water is a scarce and precious resource, faces a number of challenges. The area, even if it is a well-developed region, still suffers from rural poverty and food insecurity with a large share of the rural population living very modestly. The area of study relying strongly on the international trade, exposes regional agricultural development to volatility and fluctuations of global financial markets.

Groundwater resources extracted from the Ica-Villacuri aquifer are “transformed” into agricultural commodities which are then exported abroad as “virtual water”. Also, most of the value created in the value chain (logistics, transport, marketing and retailing) is captured abroad and the return on the capital invested by large farms is “exported” abroad, as most large farms have a financial base in western countries (Borras et al., 2020, 2012a, 2012b). The Ica Valley is therefore participating in the global value chain, via its natural capital, but with low levels of return, whilst conversely, its groundwater is undergoing increasingly high levels of marginal depletion as the profitability of the regional agricultural market grows. This implies a strong link between the international market and the local economy, which is likely to be lost in the future if groundwater collapses. This is a possibility, given the environmental fragility of the area and the dependency of the Ica Valley on foreign investment in agriculture, and would potentially results in a substantial local economic collapse as foreign capital moves elsewhere to seek greater economic returns.

The situation of the Ica Valley as shown in this paper is similar to other studies dealing with LSLA and ‘water grabbing’. For example, Raimondi and Scoppola (2022) and Chiarelli et al. (2022) have identified the strong linkage between foreign investment for land acquisition in

poor and middle-income countries and negative impacts on local water sustainability due to agricultural extension, land cover change, and technological intensification of production. As in other areas of the world, the introduction of transnational players into local contexts has resulted in growing internal conflicts among local farmers themselves due to increased competition for water which has become a rival good, whereas before it was traditionally seen as a common good (Dell'Angelo et al., 2018, 2017). As shown by Wegenast et al. (2022), LSLA that has directly affected the ecosystem and natural resource use has also interfered with social cohesion and social trust at the local level.

The current development path of the Ica Valley is a clear “win-lose” situation with divergent interests (local vs global and public vs private) and exposes the local economy to international trade through groundwater use. The water management institutions need to intervene with remedial actions, in particular, to reduce over-exploitation of groundwater using policy tools, such as water prices, local water markets, or water withdrawal permits to reduce groundwater abstraction. In combination with these policy measures, additional infrastructure, such as small dams or artificial water basins could be established to reduce pressure on water resources.

We are fully aware that our study cannot provide strong statistical evidence in terms of inference as the sample used is limited even if it is strongly representative, but it has highlighted the presence of a strong nexus between water use, food production and environmental fragility in the Ica Valley. Further studies should explore these linkages in more detail possibly by using data at smaller geographical scales. Our study is limited by a reduced number of observations due to our data and further research should explore in greater detail the correlations we found between water depletion and land concentration, crop specialization, and drip irrigation intensity.

6. Concluding Remarks

Our analysis shows that the use of water is unsustainable in the Ica Valley. The groundwater sustainability index showed that water use was significantly related to land concentration, crop specialization and drip irrigation intensity. Our study is an explorative analysis using the Ica Valley to examine the implications of tightly connected agricultural development and environmental impacts, local development, international trade, social change, and corporate

profits. In this respect, the Ica Valley is an example of a wider international pattern of trade, which exploits territories and natural resources in less developed countries, and we strongly believe that this area of research should be further explored.

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Global exports draining local water resources: land concentration, food exports and water grabbing in the Ica Valley (Peru)

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