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Rapid land cover change in agricultural valleys of the Atacama Desert, Chile

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ABSTRACT

The profound landscape modification produced by agriculture is considered one of the main threats to biodiversity worldwide. Although the main ecological impacts are likely due to agricultural expansion into natural areas, changes in crop types and production intensification also induce significant ecological changes. We studied the land cover change process in four agricultural valleys (Lluta, Azapa, Vitor and Camarones) in the Atacama Desert of Chile between 2003 and 2019, divided into four equal periods. Using spatial data and logistic regression, we assessed the driving factors of land cover change. The Azapa valley showed the highest rate of land cover change, reaching 36.4% of netting and greenhouses landscape cover by the end of the study, and 50.4% annual rate of increase during the 2007–2011 period. Intensification was observed as the anti-aphid netting cover expanded mainly in Azapa and in the last four years in Vitor and Lluta valleys. Most land cover change was related to low slopes and elevation or sites closer to roads or surrounded by already cultivated land, like agriculture expansion on barren soil or native shrubland loss. High population density was significantly correlated with land cover change ($p < 0.01$). If land cover change into netting continues as observed, it is possible that landscape homogenization occurs in the short term in almost all valleys. Anyway, disentangling how landscape change works and the involved drivers, could be useful to understand landscape simplification in arid lands that are under an agricultural intensification process.

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agricultural intensification;
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Introduction

Land use/cover change induced by agriculture, is one of the most evident expressions of the Anthropocene (Harden et al. 2014). This process is also considered a crucial driver of biodiversity loss worldwide (Sala et al. 2000; Green et al. 2005; Maxwell et al. 2016), commonly causing landscape complexity simplification (Gaméz-Virués et al. 2015). After the initial conversion of natural ecosystems into agricultural areas, further land use change usually takes place promoted by agricultural intensification, triggered

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by increases in global food demand (Tilman et al. 2011; FAO 2017a, Zabel et al. 2019), and/or by changes in the types of crops, driven by market changes (Lambin et al. 2001). Like in other types of landscape change, agriculture implies a variety of biophysical and socioeconomical drivers (Geist et al. 2006; Plieninger et al. 2016) which need to be addressed in order to understand and predict the landscape transformation process.

In recent years, agricultural intensification has accelerated worldwide (Rudel et al. 2009; FAO 2017a) with important socio-economic consequences (Scarborough 2012, Rasmussen et al. 2018), and potentially severe impacts to the environment (Foley et al. 2005; Tschardt et al. 2012; Phelps et al. 2013; Caballero, Romero, and Espinosa 2015, Cao et al. 2020). Landscape change through agricultural intensification is frequently associated to a loss of ecosystem services provision (Emmerson et al. 2016), with a consequent homogenization and simplification of agricultural landscapes (Hobbs et al. 2006; Morteo-Montiel et al. 2021). This simplification is induced by a decrease in composition and configuration complexity (Nelson and Burchfield 2021), reducing the variety of resources and crops in the landscape, exchanging heterogeneous landscapes for large monocultures or few crops. Landscape transformation and resources availability modification induced by land cover change may affect biodiversity in several ways (Sala et al. 2000; Zhang et al. 2023). In the best scenario it may provide new resources, and the species can adapt to the new features of the habitat (Rosalino et al. 2014), whereas in the worst case, landscape transformation might reduce habitat availability and alter ecological relationships, causing local species extinctions (Williams et al. 2021).

An extreme example of agricultural intensification is the use of netting, greenhouses, and other types of covered crops. These types of land use usually require full vegetation clearance, severely decreasing the available habitat area and reducing landscape heterogeneity. The socioecological implications for landscape and biodiversity of netting and greenhouses have been widely addressed in the literature (Mota et al. 1996; Pérez, López, and Fernández 2002; Caballero, Romero, and Espinosa 2015; FAO 2017b; Oliva 2017).

Landscape change is usually considered a multivariable phenomenon (Tahmasebi, Karami, and Keshavarz 2020; Xu et al. 2020), oriented by multiple biophysical variables such as topographic features of the landscape, proximity to urban centers and roads, vegetation type, or local climate (Lambin et al. 2001; Rodríguez, Armenteras-Pascual, and Retana 2013) and anthropogenic conditions such as human population density or urbanization (Hadush, Holden, and Tilahun 2019; Adjei et al. 2023). Landscape changes in arid lands can be very critical, because of the scarcity and spatial concentration of vegetation, and the level of threat and/or endemism of biological communities (Ibarguchi 2014; Zhang et al. 2023). Water is also commonly limited, restricting the expansion of crops into new areas, likely forcing agricultural intensification to meet the increasing demand for food. However, the problem of landcover change in desert ecosystems has received relatively little attention (Zak et al. 2008; Salazar et al. 2015)

The Atacama Desert in northern Chile is considered one of the driest places on Earth, with some areas receiving no precipitation in decades (Henríquez 2013). Despite the latter, rainfall in the highlands (> 4,000 m a.s.l.) allows some water to reach the ocean through narrow “oasis-type” valleys. These valleys are surrounded by an extremely

arid and rugged land, leaving limited options for agricultural expansion or another type of land use. In addition, some valleys of the region have high levels of salinity and boron concentration in soil and water, reducing the variety of suitable crops to grow (Torres and Acevedo 2008). In order to study the evolution of land cover change in this desert region, we analyzed four valleys with different levels of agricultural development over a period of two decades. Specifically we aimed at testing the hypothesis that land cover change in the agricultural valleys of Arica and Parinacota region has been mostly oriented to intensification rather than to the expansion of the cultivated areas. We also predicted that most changes are related to some common biophysical drivers of the landscape such as elevation and to socio-ecological factors such as human population density.

In addition to the scarcity of information on land cover change patterns in arid and semiarid areas, there is also a specific lack of research on the evolution of land use in already modified landscapes like agricultural systems.

We were also interested in providing more evidence about the transformation of traditional agroecosystems into technology-intensive crops, and to discuss the implications of this phenomenon for biodiversity conservation.

Study area

The study area is located in the Arica - Parinacota region, in the Atacama Desert of northern Chile. We focussed on the four northernmost valleys: Lluta, Azapa, Vitor and Camarones, from north to south (Figure 1). This region is dominated by an absolute desert, but it is crossed by narrow flat valleys that carry water from the

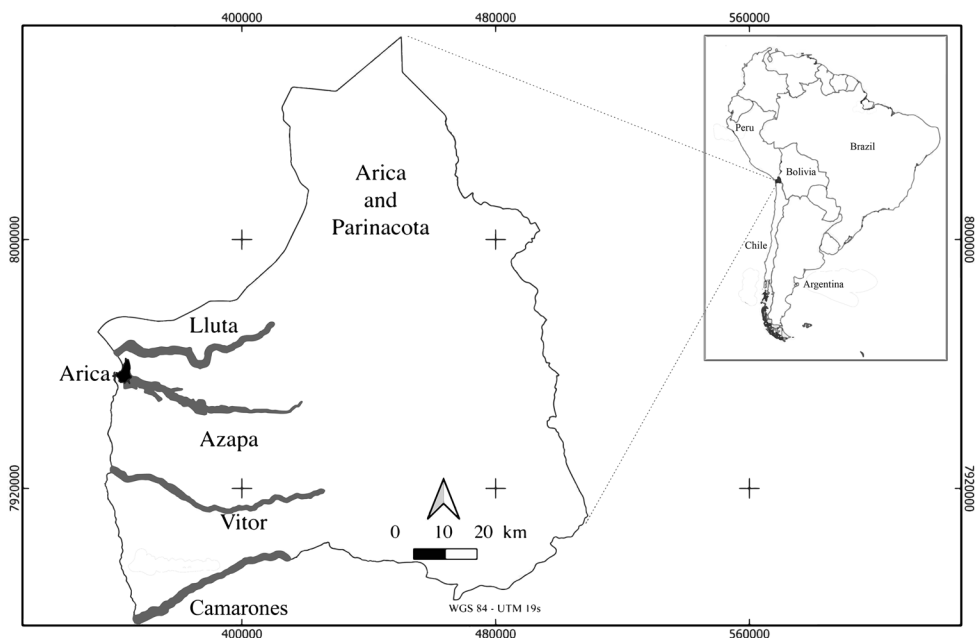


Figure 1. Map of the study area, showing the main four valleys of the Arica And Parinacota region in northern limit of Chile (coordinates system WGS84-UTM 19s).

highlands, which, in turn, allow the existence of native shrubland vegetation. According to the International Vegetation Classification the macrogroup vegetation type for these valleys correspond to “Sechura Atacama Semi-Desert Riparian Scrub, (Faber-Langendoen et al. 2014) and the specific zonal vegetation unit type is defined as “Tropical interior thorny forest of *Geoffroea decorticans* - *Prosopis alba*” (Luebert and Pliscoff 2006, 2022). The vegetation is accompanied with other native threatened species (IUCN Conservation Category) as *Morella pavnis* (EN), *Haplorhus peruviana* (VU) and *Vachellia macracantha* (LC). These natural plant formations are very threatened and poorly represented in the national system of protected areas (Pliscoff and Fuentes-Castillo 2011).

There are some important differences between the biophysical, economic, and agronomic features between the four valleys (Table 1). Topography is similar in all study sites, because the four valleys are formed by narrow strips of flat land surrounded by slopes of sand and rock with a West-East elevational gradient. Entisols are the most common soil type in these valleys (IUSS Working Group WRD, 2022) with some of them showing high salinity level and ions concentration. Climate is appropriate for the cultivation of a vast variety of crops, vegetables, and fruits (González et al. 2013) as temperatures vary between 15°C and 25°C all year long. Agriculture is a very profitable activity for local farmers and represents the principal market and provider of vegetables for almost the whole country during the austral winter (Riquelme et al. 2013). Annual precipitation in the valleys is minimal (0–2.6 mm) but it increases with elevation (Meseguer-Ruiz et al. 2019). Thus, most of the water used for agriculture and other human needs is supplied by rivers (e.g., San José river in Azapa) that are fed by the summer precipitation in the Andean highlands. Despite the water availability of these rivers, in Lluta and Camarones the high water and soil salinity limits the variety of cultivable crops (Torres and Acevedo 2008).

In 2017, human population in the region was approximately 226,000 inhabitants (Yañez 2018), with most people living in the city of Arica and the Azapa valley. Human population density varies significantly among the four valleys: Lluta (28.9 people/km²), Azapa (198.6 people/km²), Vitor (24.1 people/km²) and Camarones (8.2 people/km²).

Agriculture in the study area began 3,000 years before the present, with the domestication of crops such as potatoes, tomatoes, pumpkins, and maize (Rivera 1983; Manzur and Alanoca 2012; García and Santoro 2014). Presently, the agriculture of these valleys is dominated by annual crops, such as tomatoes, the Lluteño corn (*Zea mays*, amilacea type), a variety adapted to salinity conditions of Lluta valley (Bastías et al. 2011), and

Table 1. Biophysical characteristics, socioeconomic conditions, and agronomical traits of four valleys in the Atacama Desert of northern Chile.

Features	Lluta	Azapa	Vitor	Camarones
Soil salinity*	High	Low	Low	High
Water salinity*	High	Low	Low	High
Inhabitants**	2152	25727	869	440
Urban or Rural***	Rural	Urban/Rural	Rural	Rural
River*	Lluta (permanent)	San José (permanent)	Codpa (seasonal)	Camarones (permanent)
Water pH***	7.9	7.5–7.9	7.47	7.8
Property owners****, °	Large	Small and large	Small and Large	Large

*González et al. (2013), **www.censo2017.cl, ***Torres and Acevedo (2009), ****Tapia and Vásquez (2009), °Tapia and Vega (2009).

by olive groves (*Olea europaea*), which are cultivated since the sixteenth century in Azapa (Sepúlveda and Tapia 2018).

The warm and stable climate that favors the development of agriculture, also promotes the dissemination of many pests which affect most crops (Tello 2017). For this reason, growers have traditionally resorted to the use of significant pesticides amounts (Tapia and Vega 2009). However, during the last decade, anti-aphid netting has been introduced to reduce infection without the use chemicals (Oliva 2017), and to reduce the use of irrigation, due to a reduction in evapotranspiration (Riquelme et al. 2013).

Methods

For this study we worked with the concept of land cover because it can be defined by direct observation of the landscape surface, in contrast to land use, which requires some sort of socioeconomic assessments to define the usage of the territory (Fischer, Comber, and Wadsworth 2005). In order to quantify land cover change, we adapted the method used by Uribe, Estades, and Radeloff (2020), performing a photointerpretation of yearly satellite images from 2003 to 2019, using a systematic 400 × 400-m grid of sampling points created with QGIS 3.16.6 tool. A total of 1827 points were distributed over the four valleys according to their area and shape (Lluta: 468, Azapa: 806, Vitor: 218, Camarones: 335). These systematic grids allowed us to perform estimations of the point-level probability of cover change over time.

Photointerpretation was conducted using Google Earth Pro satellite imagery from 2003 to 2019, due to its image accuracy, representativeness, and ease of visual interpretation (Cha and Park 2007; Barbosa and Campos 2011; Ghorbani and Pakravan 2013). For each year, we superimposed the grid of points over one of the available satellite image sets (preferably spring) with the best image quality and definition (cloudless and lightening enough to observe the most detailed surface cover), then determined the land cover for each point manually, through a detailed observation considering texture, color, and landscape patterns. We defined a specific land cover class for every point yearly in each valley. The photointerpretation was conducted using an eye observer elevation of 100 to 1000-m. For better accuracy and to facilitate the visual differentiation between land cover classes assignment, ground truthing was available for some sample points (≈ 200) and most years. Only one trained observer (MC) determined the class of land cover for all the points of the complete imagery set and sample.

For each point, in each of the images used we assigned one of ten land cover classes that correspond to the class observed at the specific coordinates. Land cover classes were defined according to Zhao et al. (2016) and are as follow: barren soil (BS), native shrubland (NS), grassland or pasture (GL), water (WA), buildings (BU), anti-aphid netting and greenhouses (NG), low crops and vegetables (LC), fruit groves including olives (FG), corn (CN) and set-aside or fallow (SA). Barren soil is a type of land cover with no evidence of vegetation, specifically natural desert lands. On the other hand, set-aside is a land cover class that shows evident patterns of arable abandoned lands, like parallel lines over the soil without vegetation, or previous low crop cover. Grasslands and native shrublands are natural vegetation types dominated by grasses and shrubs, respectively. Low crops are a large variety of cultivated types that are not

trees, such as tomatoes, peppers, pumpkins, zucchinis, and lettuces or alike. Water land cover corresponded to natural water bodies and artificial reservoirs.

To accommodate for potential agricultural expansion over the years, and to allow for neighborhood analyses, we included in our sampling a 400-m buffer area around the vegetation limits of each valley in 2003. For this reason, our sample included a disproportionate amount of barren soil (40–50% of each valley).

Additionally, for each point we obtained some potential biophysical predictors of land cover change, such as latitude and longitude (UTM 19s), slope (0.5–76.6%), and elevation (0–2023.4 m), calculated from a Digital Elevation Model (DEM) downloaded from the USGS Earth Explorer server (<https://earthexplorer.usgs.gov/>). We also calculated the minimum distance to the nearest public road (0.1–7456.5 m), and the proportion (0–100%) of the ten land cover classes among the eight neighboring sampling points. The latter proportions were calculated for each of the analyzed years. For all geoprocessing, we used QGIS 3.16.6 (Graser 2016). For area calculations, we assumed that each point represents a 16-ha area (400×400-m).

In order to assess the land cover change and agricultural intensification, we divided the studied time into four periods of five years, between years 2003, 2007, 2011, 2015 and 2019. For all the latter we performed cross-tabulation analyses and generated transition matrices (Nahuelhual et al. 2012; Uribe, Estades, and Radeloff 2020) in order to describe the exchange percentage of every land cover class between the ten land cover classes in the four periods (Supplementary Table 1). We also estimated the annual rate of change for every land cover type and period, including the rate of change between the first and last study year (Supplementary Table 2).

After some exploratory analyses, we decided to focus on four types of changes as the dependent variables, all of them related to agricultural expansion and/or intensification: A. loss of native shrubland (i.e., NS replaced by any other class), B. agricultural expansion into barren soil (i.e., any agricultural use replacing BS), C. increase of open low annual crops (i.e., LC replacing any other land cover class) and D. increase of areas covered with anti-aphid netting and greenhouses (i.e., NG replacing any other land cover class). For changes C and D, in addition to the described predictors, we considered the land cover class of the point at the beginning of the period as a potential explanatory variable.

To explain the observed changes in terms of biophysical drivers, we related the probability of change to the landscape predictors (including “valley” as a factor) using logistic regressions (Zuur et al. 2009). For each point we produced four binary variables reflecting the occurrence of the four types of change separately, with value one for change and value zero for no change, considering all the changes occurred in every period. To build the models we used each one of the four types of change as the dependent variable and all the biophysical covariables related to the point, year, and valley, as the explanatory variables. Then, we performed the logistic regressions with binomial family. In order to avoid multicollinearity, a correlation test was performed before regressions, and for each pair of variables with correlations over 0.6, one was excluded. The best model for each period and type of change was obtained through forward and backward stepwise procedures comparing the Akaike Information Criterion and selecting the lower value with their respective estimators (Cavanaugh 1997). Because we did not have access to local human population density for each of the four periods,

in order to relate such variable with total land cover change rate we conducted an analysis at the valley level ($n=4$) for the entire study period. We restricted the latter analysis to the period 2003–2017, because the latest available census data was for 2017 (<http://www.censo2017.cl/>). For all statistics analyses we used RStudio 1.4.1106.

Results

In general, Azapa showed the highest rate and amount of land cover change among the four studied valleys in the whole study time. It was followed by Vitor and Lluta, and finally, Camarones, which did not show any significant change in sixteen years (Figure 2). The most conspicuous of such land cover changes involved the steep increase of anti-aphid netting in Azapa, starting around the year 2011, and reaching 36.4% of the valley land cover (excluding hillside barren soil) by the end of the study period (Figure 2). This change was in detriment of other land cover classes, such as low annual crops, fruit groves, native shrublands and barren soil. More than 1400 ha of barren soil were transformed and changed to a human-induced land cover like netting and low crops.

The main land cover decrease occurred in Azapa as well, involving a reduction of more than 50% of the area covered by fruit groves from 2003 (2000 ha) to 2019 (928 ha). Also, in Vitor an important decrease of native shrubland was observed since 2007, resulting in an increase of low crops, netting, buildings, and water reservoirs. In Lluta, the main changes were the reduction of native shrublands area and an increase of low crops cover (Figure 2).

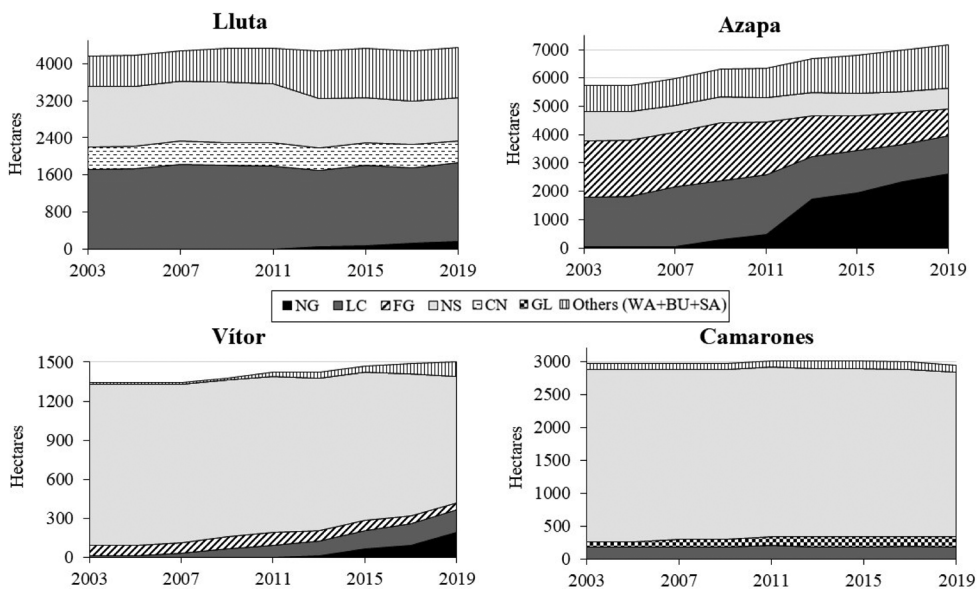


Figure 2. Land cover area (ha) for four valleys in Northern Chile from 2003 to 2019. Barren soil (BS) is not included to highlight extensification in Azapa and Vitor. Native shrubland (NS), grasslands (GL), water (WA), buildings (BU), anti-aphid netting and greenhouses (NG), low crops and vegetables (LC), fruit and olive groves (FG), corn (CN), grassland (GL), and set-aside (SA).

Different types of changes had different temporal dynamics in the studied valleys (Figure 3), although there was a slight trend for higher change rates to concentrate on the second and third periods (2007–2015).

The largest loss of native shrublands occurred in Lluta in the third period followed by Vitor in the last period (Figure 3A). Vitor was the only valley that showed a positive and almost constant tendency for increasing annual crops and loss of native shrublands area along the four periods (Figure 3A and 3C).

Among the four valleys, Azapa experienced the larger expansion of agriculture over barren soil, reaching more than 150 ha per year in the second and third periods (Figure 3B). Also in Azapa, annual crops cover showed the largest increased area with more than 150 ha per year in the third period (Figure 3C). Moreover, in Azapa agricultural intensification, represented by the transition from any land cover class to netting, was the largest change observed among all types of transition, affecting a high proportion of the valley throughout the years of the study, reaching approximately 400 ha per year during the third period. (Figure 3D).

In Azapa, anti-aphid netting showed a mean annual rate of increase of 24.7% during the 17 years of study, reaching a 50.4% during the second period (Figure 4). Lluta and Vitor had negligible netting or greenhouse cover before the third period, but in the last period it showed an elevated annual rate of change of 22.9% and 27.5%, respectively. Low crops in Vitor showed a high annual rate of change for the first and second periods of 17.3% and 27.5%, respectively. Diverse land cover showed a negative rate of change in different periods, but the higher values were a 12.8% of fruit groves loss during the fourth period in Vitor, followed by a 10.6% of fruit groves loss during the third period in Azapa (Figure 4). Full results of annual rate of changes are shown in Supplementary Table 2.

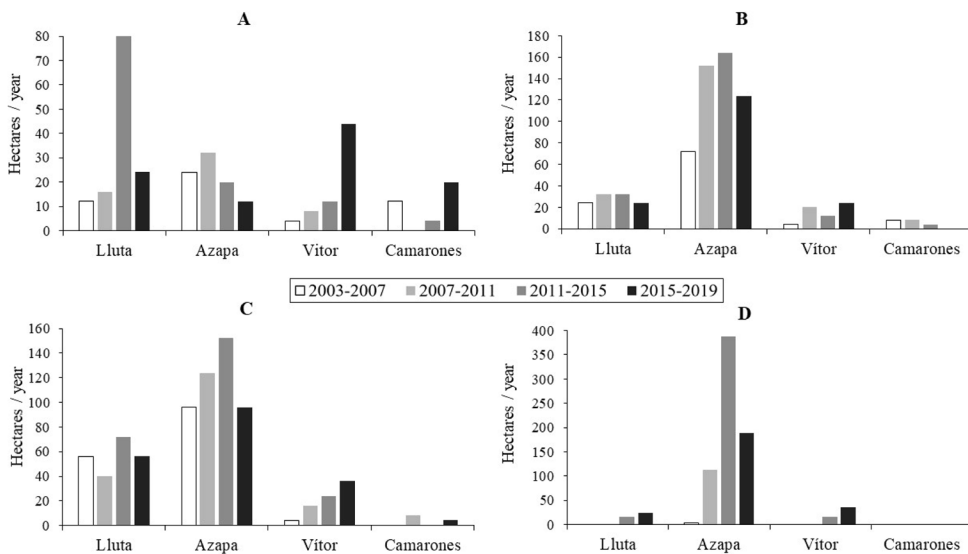


Figure 3. Annual estimated land cover area transformed in four time periods, for four valleys in Northern Chile. A: Native shrubland loss, B: Agricultural expansion on barren soil, C: Increase of low annual crops, D: Expansion of anti-aphid netting and greenhouses.

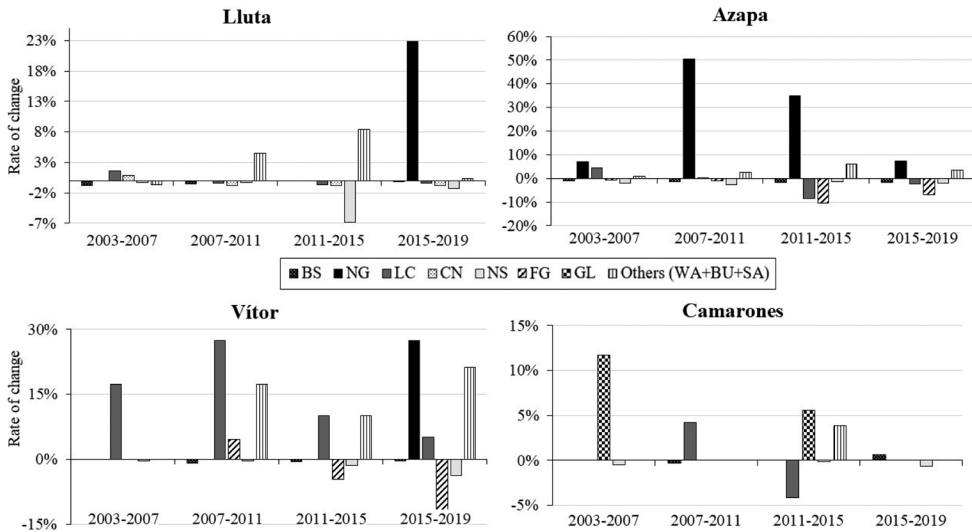


Figure 4. Estimated annual rates (percentage) of land cover change per 4-years period in four valleys in Northern Chile. Barren soil (BS), native shrubland (NS), grasslands (GL), water (WA), buildings (BU), anti-aphid netting and greenhouses (NG), low crops and vegetables (LC), fruit and olive groves (FG), corn (CN), grassland (GL), and set-aside (SA).

Logistic regressions showed that different land cover changes were driven by different biophysical variables, and that some of these relationships changed between periods (Table 2A). The loss of native shrubland during the first three periods was negatively affected by the proportion of barren soil ($p < 0.001$) and native shrubland ($p < 0.05$) in the surroundings. In the last two periods, change occurred more often at lower altitudes ($p < 0.05$) and in areas closer to roads ($p < 0.05$). Also, during the third period this type of change was significantly more important in Lluta, in contrast with Camarones which showed the opposite behavior ($p < 0.05$).

During the four studied periods, agricultural expansion occurred more frequently in places with lower slopes and less proportion of barren soil and native shrublands in the surroundings ($p < 0.001$ – 0.01). Also, for the last three periods, this type of change was less likely to occur in Lluta and Camarones, in contrast to Azapa or Vitor, where it was more probably to occur (Table 2B).

Intensively managed low crops were more commonly established at places with lower slopes and areas identified as fallow/set aside, in all periods ($p < 0.01$ – 0.05). In addition, sites in Lluta and Camarones were less likely to change into low crops (Table 2C).

During the first period of this study, the factors influencing the expansion of anti-aphid netting and greenhouses could not be evaluated because of negligible change. For the following periods, however, low crops cover was more likely to change into netting ($p < 0.001$). During the three assessed periods, this change was more likely to occur in Azapa ($p < 0.001$) and in the last two periods this change was mostly associated to low slope areas ($p < 0.001$) (Table 2D).

When relating the human population density (log-transformed) and the total land-cover change rate for the period 2003–2017 (Figure 5), we observed a significant positive relationship ($p < 0.01$).

Discussion

There is a general lack of land cover change assessments for agricultural landscapes in arid or semi-arid lands in South America (Salazar et al. 2015), in contrast to the abundance of studies on agricultural expansion and deforestation within grasslands, forests, and tropical dry forests (Grau, Gasparri, and Aide 2005; Zak et al. 2008; Huang et al. 2009; Caldas et al. 2013). Our results showed significant variation in land-cover change rates in the studied desert valleys. Thus, while Azapa experienced a rapid change during the past two decades, Camarones remained mostly unchanged throughout the studied years. As can be expected for an oasis-type of productive systems (Guogang, Degang, and Xinhuan 2012), most changes occurred in areas already modified by people, frequently reflecting an agricultural intensification process, confirming our hypothesis.

In Azapa, most technification of crops followed a three-step land cover sequence, with barren soil changing into open low crops, which were later replaced by netting. Another observed sequence of land cover change starts with olive and/or fruit groves that are later changed into low crops, and finally into netting. Both sequences of land

Table 2. Best generalized linear models to explain the probability (binomial family) of four evaluated land cover change types (2.A, 2.B, 2.C, 2.D), in four valleys in Northern Chile, for four times periods. Bold fonts are used to identify variables with significant effects ('****' 0.001, '***' 0.01, '**' 0.05) on the dependent variable (probability of land cover change). The sign before each variable indicates the direction of the effect. AICc: Akaike Information Criterion, corrected for degrees of freedom. Llu: Luta, vit: Vitor, cam: Camarones, valley: any of the four valleys, slp: slope, ele: elevation, dist: distance to nearest road, BS: barren soil, NS: native shrubland, GL: grasslands, WA: water, BU: buildings, NG: anti-aphid netting and greenhouses, LC: low crops and vegetables, FG: fruit and olive groves, CN: corn, GL: grassland, and SA: set-aside. For land cover classes, suffix "o" refers to land cover at the point in the first year of the period, and "n" refers to the average percentage of land cover in the neighborhood.

Period	2.A. Native shrubland loss (NS replaced by any other class)	AICc	p-value	R ²
2003–2007	- BS ⁿ *** - WAn - NS ⁿ *	103.89	0.74	0.16
2007–2011	- Valley + BS ⁿ * + WAn* + BU ⁿ * + LC ⁿ * + FG ⁿ * + NS ⁿ * + SAn*	98.32	0.01*	0.37
2011–2015	Valley - Ele* - Dist* + BS ⁿ * + WAn + BU ⁿ + NG ⁿ * + LC ⁿ * + FG ⁿ * + CN ⁿ * + NS ⁿ *	153.11	0.02*	0.39
2015–2019	Valley - Ele** - Dist* - FG ⁿ	151.72	0.37	0.23
Period	2.B. Agriculture expansion on barren soil (BS replaced by any agricultural cover)	AICc	p-value	R ²
2003–2007	- Slp** - BS ⁿ *** - WAn - BU ⁿ - FG ⁿ - NS ⁿ * - SAn	220.6	0.07	0.16
2007–2011	- Slp*** - Dist - BS ⁿ ** - WAn - BU ⁿ - CN ⁿ - NS ⁿ **	348.32	0.19	0.18
2011–2015	Valley (- Llu* - Cam*) - Slp*** + NG ⁿ + LC ⁿ + FG ⁿ + NS ⁿ	323.08	0.00024***	0.24
2015–2019	Valley (- Llu***) - Slp*** - Ele - BS ⁿ ** - BU ⁿ * - NG ⁿ *	269.68	0.01*	0.26
Period	2.C. Intensive low annual crops increase (replacing any land cover with LC)	AICc	p-value	R ²
2003–2007	- Valley - Slp** - FG ^o ** + SA ^o ** - BS ⁿ *** - WAn - BU ⁿ - FG ⁿ - SAn	300.13	0.4	0.29
2007–2011	Valley (- Llu* - Cam*) - Slp* - Dist - FG ^o * + SA ^o ** + LC ⁿ	400.4	<0.001***	0.13
2011–2015	Valley (- Llu* - Cam*) - Slp** - Ele* - GL ^o * + SA ^o *** + BS ⁿ ** + LC ⁿ ** + FG ⁿ * + CN ⁿ * + NS ⁿ *** + SAn**	437.39	0.0001***	0.25
2015–2019	Valley (- Cam*) - Slp** + Dist + SA ^o *** + BU ⁿ	356.67	<0.001***	0.25
Period	2.D. Anti-aphid netting and/or greenhouses increase (replacing any land cover with NG)	AICc	p-value	R ²
2007–2011	- Valley + LC ^o *** - NS ⁿ	195.42	<0.001***	0.42
2011–2015	- Valley (Llu*** Vit*) - Slp** - Ele* + LC ^o *** + NG ⁿ + LC ⁿ	466.12	0.002**	0.48
2015–2019	Valley (- Llu***) - Slp* - Ele - Dist + LC ^o ***	387.43	<0.001***	0.33

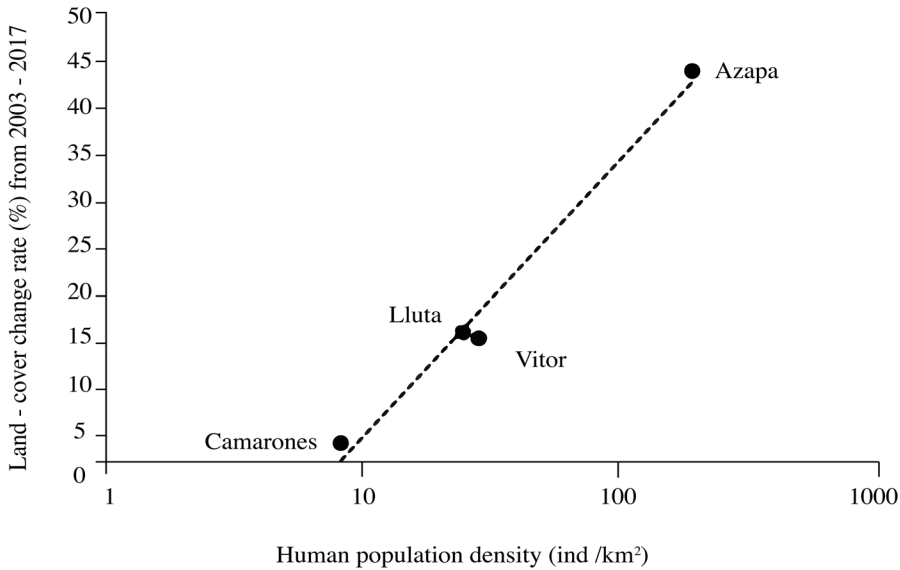


Figure 5. Relationship between average human population density (2017) and land-cover change rate (2003–2017) for four agricultural valleys in northern Chile.

cover change are oriented to intensification of production and are profit driven, because netting allows a noteworthy increase of mean production (Riquelme et al. 2013; González et al. 2013). Although at much lower pace, Lluta and Vitor seem to be following Azapás trend, showing some of the initial stages of intensification processes, and it is likely that Camarones may start to undergo the same change in the near future, possibly induced by the know-how development as the initial experience with the low crops and then the improvement into netting.

Our results showed that most land cover change was due to agricultural technification, some expansion over absolute desert lands was also recorded. The latter transformation from barren soil to cultivable lands requires a large input of resources, such as water, irrigation infrastructure and fertilizers, inducing a rapid intensification process due to the increase of netting over desert.

The slight reduction in the rate of agricultural expansion observed in Azapa during the last studied period (2015–2019), is in accordance to a deacceleration of the rate of land use change observed throughout South America in the same period (Winkler et al. 2021). But, along to the effects of economy and market demands, in the studied valleys this pattern may be due to a growing scarcity of natural areas available from conversion to agriculture and to the development of intensive agriculture, using less area but with higher productivity systems.

As predicted, land cover change rate was strongly correlated with human population density, reflecting the importance of the population pressure as a driver of agricultural intensification (Geist et al. 2006; Serra, Pons, and Saurí 2008; Rodríguez et al. 2013; Hadush, Holden, and Tilahun 2019). Factors such as market size and the density of roads may be mechanisms that stimulate a faster land use change in agricultural regions with higher populations (Braumoh and Vlek 2005, Kleemann et al. 2017).

One of the most striking aspects of the studied land cover change was the rapid irruption of anti-aphid netting in 2011. This production system is directly related to increases in productivity and income for local farmers, with significant savings in irrigation and agrochemical use, and a reduction of losses due to pests (Tapia and González 2014). The abrupt increase of anti-aphid netting usage observed in Azapa during the third and fourth periods could be related to the effect of a study published by Riquelme et al. (2013), who conducted a field experiment on the use of this cultivation technology with tomatoes and sweet peppers, showing an important reduction of water and pesticides input with a remarkable increase of productivity. These findings spread rapidly among local farmers, increasing netting use. The annual growth rate of netting cover observed in Azapa (25%) is even higher than the world's average of 20% annual growth rate of the use of greenhouses and netting-covered crops since 1980 (Pérez, López, and Fernández 2002).

In many temperate regions, this practice has had a controversial impact on the environment and landscapes (FAO 2013, 2017b; Caballero, Romero, and Espinosa 2015). Although direct benefits of netting include an important reduction of the use of agrochemicals (Berny 2007; Gupta 2019), and an improved efficiency in the use of irrigation water (Riquelme et al. 2013), these structures represent an extreme transformation of the landscape, both esthetically and ecologically. The virtual disappearance of any type of vegetation and substrate remotion underneath an artificial cover eliminates the habitat for most wildlife adapted to open agricultural environments. The latter could lead to a biotic homogenization process, simplifying the structure and composition of the landscape (Hobbs et al. 2006; Gaméz-Virrués et al. 2015). Particularly, in the valleys studied by us, the increased cover of anti-aphid netting is associated to an important decline in the abundance of many farmland birds (Castillo and Estades, in preparation).

Some of the biophysical drivers of agricultural intensification and land cover change found by us, such as, elevation and slope, are also common in other agricultural arid and semi-arid lands (Luo et al. 2020). These topographic features, along with human-made elements of the landscape such as roads, are relevant to the accessibility to the land, facilitating land cover change. Also, socioeconomic factors like markets and local policies (e.g. state-sponsored projects to promote the development of a particular region) are important drivers of landscape change oriented to intensification (Lambin et al. 2001; Ceddia et al. 2014). Following the declaration of the Arica and Parinacota region as a Fruit-fly (*Ceratitis capitata*, Wiedemann 1824) free zone in 2004, a diversification and expansion of crops was observed, because before that date only tomatoes were suitable to be commercialized outside the region (Mazuela et al. 2009). This policy also induced the increase of human population in some valleys, with an important work migration to rural areas related to agricultural technification and extensification, especially in Azapa.

Half a century ago, the studied valleys were dominated by traditional and extensive farming, mostly olive and other fruit groves (particularly in Azapa and Vitor), conforming a complex vertical structure which allowed the presence of a varied wildlife, particularly birds (Rottmann 1972). But the current land cover is dominated by few types of covered crop and anthropic structures such as anti-aphid netting, buildings, and water reservoirs, restricting the presence of native fauna, due the reduction of available habitat area as native shrublands. These changes in the ecosystem structure and composition may prove critical for some habitat specialist species (Gil-Tena et al.

2015; Jeliaskov et al. 2016). Indeed, in the last three decades, the Chilean woodstar (*Eulidia yarrellii*, Bourcier 1837), an endemic hummingbird of the Atacama Desert, went from being a rather common species to being considered Critically Endangered (BirdLife International 2020), because of its drastic population decline (Estades, Lazzoni, and Aguirre 2019). The latter has been particularly severe in the Azapa valley, in which the species has not been seen for many years, whereas the remaining populations are located in the less intensively managed valleys such as Vitor and Camarones (Estades, Lazzoni, and Aguirre 2019). This reduction has been attributed mostly to the loss of native shrubland and olive groves, which have been replaced by annual crops, mostly under netting. Indirectly, the level of intensification of the agriculture in some areas of the valleys has significantly raised the price of the land, making the acquisition of land for conservation an increasingly difficult task.

Conclusion

The four analyzed valleys, with their different degrees of human perturbation and socio-ecological features, represent a suitable study case to assess the land cover change in arid agricultural landscapes. This work provides some understanding of the patterns and mechanisms of land cover change in oasis-type agricultural valleys, in which the land available for cultivation is severely limited by aridity and topography. These results should be useful for landscape planners and conservation managers in arid regions, by providing some predictive tools regarding the areas where changes are most likely to occur. They also show that planning should consider scenarios of high dynamism in terms of land cover, particularly in areas with high population density.

Conservation of biodiversity in arid agricultural valleys such as the ones we studied, will likely require new policy regulations to allow for the compatibility of production intensification and the maintenance of minimal levels of naturalness. Our study shows how the unregulated shift from traditional cultivation practices to technology-intensive production systems, may have undesirable ecological impacts, even when the new technology may be more efficient in the use of water and agrochemicals.

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Disclosure statement

The authors declare having no conflict of interest.

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