Agricultural Development, Smallholder Support and Natural Land Cover in Chile

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Agricultural Development, Smallholder Support and Natural Land Cover in Chile

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Abstract

Agriculture plays an important role in maintaining rural livelihoods and landscapes, but agricultural development can also increase pressure on natural land cover. This article investigates this relationship in Chile by considering three dimensions of agricultural development: commercial agricultural area, agricultural output per unit of land, and public support to small-scale producers. Annual data for the period 2000–2022 are analysed using fully modified cointegrating polynomial regression and an error-correction model. The results show that commercial agricultural area is negatively associated with natural land cover, while agricultural output per unit of land presents a positive association. Public support for small-scale producers presents a U-shaped association with natural land cover: increases in support are associated with lower natural land cover below the estimated turning point and with higher natural land cover above it. The error-correction coefficient is negative ($\lambda = -0.534$) and statistically significant at the 5% level under conventional standard errors ($p = 0.0127$), although significance is retained only at the 10% level under HC3 robust standard errors ($p = 0.0506$). This suggests conditional evidence of adjustment towards the estimated long-run relationship, subject to the inconclusive cointegration tests. Complementary tests provide inconclusive evidence of cointegration, implying that the estimated long-run relationships should be interpreted as conditional associations rather than causal effects. These results show that dimensions of agricultural development can be associated with natural land cover differently, suggesting that productive, social and environmental objectives need to be considered jointly in designing and evaluating agricultural and rural development policies.

Keywords: natural land cover; commercial agriculture; small-scale farming; agricultural policy; cointegration

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1. Introduction

Agriculture has traditionally played an important role in shaping rural landscapes. These landscapes are not only areas where food and other agricultural products are produced, but also the result of long periods of interaction between rural communities and their surrounding environment. In this context, agriculture can contribute to maintaining cultural landscapes, rural heritage and other values that extend beyond its productive function [1–5]. However, agricultural development can also transform these landscapes. Agricultural expansion requires land and may therefore compete directly with forests, shrublands and other forms of natural cover, while agricultural intensification can generate additional pressures on biodiversity and ecosystem functions [6,7]. This creates a potential conflict between increasing agricultural production and maintaining the ecological and cultural characteristics of rural landscapes.

Small-scale agriculture occupies an interesting position within this conflict. Small and family farms are frequently associated with traditional practices, local knowledge and landscape heterogeneity [8,9]. However, their environmental effects depend on the way in which land is used and on the incentives faced by farmers [10–12]. As a result, the contribution of small-scale agriculture to rural traditions does not necessarily imply that increasing or maintaining its productive activity will always have positive effects on natural land cover. This issue is particularly relevant when public policies are considered. In Chile, the Instituto de Desarrollo Agropecuario (INDAP) provides different forms of support intended to improve the productive and economic conditions of small agricultural producers [13–15]. At the same time, Chile has developed a highly commercialised agricultural sector characterised by important processes of modernisation and market integration [16,17]. Public support to small producers therefore operates within a broader process of agricultural development. Policies supporting small producers can contribute to maintaining rural livelihoods and agricultural activities. However, by facilitating investment, improving productive capacity or maintaining farming activities that otherwise might be abandoned, they may also affect the way in which agricultural land is used [18–20]. This creates a possible policy trade-off. Support can be successful in strengthening small-scale agriculture and rural communities while, at the same time, contributing indirectly to pressures on natural land cover.

Existing research provides important evidence on different parts of this problem. Agricultural expansion and intensification have been studied in relation to their environmental consequences [21,22], while other research has examined the contribution of traditional agriculture and local knowledge to cultural landscapes and environmental management [23,24]. Agricultural support policies, on the other hand, have been investigated mainly in relation to their productive, economic and social effects [25,26]. Less attention has been given to how these processes interact over time and whether their combined effects become part of the long-run evolution of rural landscapes. This distinction is important from a policy perspective. A temporary change in natural land cover and a persistent change have different implications. If agricultural development and policies supporting small producers are associated with the long-run evolution of natural land cover, their environmental implications may extend beyond their immediate effects. As a result, natural land cover can reflect not only changes associated with commercial agricultural development, but also the consequences of policies originally designed to achieve productive and social objectives. This suggests that agricultural support and environmental objectives may need to be considered jointly rather than as independent dimensions of rural development.

Conceptually, the relationship between agricultural development and natural land cover can be understood through three interconnected dimensions. First, the spatial expansion of commercial agriculture may compete directly with natural vegetation for land. Second, increases in agricultural output per unit of land may reduce the need for further agricultural expansion, although greater productivity may also create incentives for additional land conversion. Third, public support to small-scale producers may influence land-use decisions by facilitating productive investment, maintaining existing agricultural activities or encouraging changes in production. The environmental implications of these mechanisms are not necessarily uniform, and their relative importance may vary over time. This provides the conceptual basis for examining the three dimensions jointly, without imposing predetermined directional relationships between agricultural development and natural land cover.

Chile provides an appropriate case to investigate this issue because commercial and small-scale agriculture coexist within a country characterised by considerable ecological diversity and important changes in agricultural production and land use [27–29]. In considering this context, the objective of this article is to investigate the long-run relationship

between agriculture and natural land cover in Chile. Three dimensions are considered: the area under commercial agriculture, agricultural output per unit of agricultural land, and non-reimbursable public support directed towards small-scale producers. These three dimensions are selected to distinguish between different aspects of agricultural development: the spatial extent of commercial agricultural activities, the intensity of agricultural output relative to land use, and public support directed towards small-scale producers. They are not intended to provide an exhaustive explanation of changes in natural land cover, but to examine whether these distinct productive and policy-related dimensions exhibit different associations with its evolution.

These considerations motivate three hypotheses concerning the relationship between agricultural development and natural land cover.

H1. *Commercial agricultural area is expected to be negatively associated with natural land cover. Agricultural expansion increases competition for rural land and may occur at the expense of natural vegetation [4,20].*

H2. *Agricultural output intensity is expected to be associated with natural land cover, although its direction is theoretically ambiguous. Greater output from land already under agricultural use may reduce the need for further expansion, consistent with a land-sparing mechanism, whereas increased agricultural profitability may encourage additional land conversion [20,30].*

H3. *Public support to small-scale producers is expected to exhibit a potentially non-linear association with natural land cover. Support may relax productive constraints and encourage agricultural activity, while the marginal response to additional assistance and its land-use implications may vary with the level and characteristics of support [30–34].*

The empirical specification is deliberately parsimonious. Although changes in natural land cover may be associated with additional environmental, economic and demographic factors, the analysis focuses on these three dimensions because they directly represent the productive and policy-related processes examined in this study. Furthermore, the availability of 23 annual observations imposes important constraints on model complexity. Incorporating additional explanatory variables would reduce the available degrees of freedom and could increase estimation uncertainty. The selected specification therefore reflects a balance between theoretical relevance, empirical feasibility and model parsimony, rather than an attempt to explain all determinants of natural land-cover change. Other factors, including climatic variability, urban expansion and international agricultural commodity prices, may also be associated with changes in natural land cover. Their exclusion means that the estimated coefficients may be affected by omitted-variable bias where these factors are correlated with the explanatory variables, reinforcing the need to interpret the findings as conditional associations rather than causal effects.

Annual data for 2000–2022 are analysed using cointegrating polynomial regression and complementary cointegration tests to examine their estimated long-run relationship, together with an error-correction specification to examine short-run dynamics conditionally on that relationship.

2. Methodology

2.1. Study Area and Data

Chile has considerable geographical and climatic diversity across its territory, reflected in major differences in natural vegetation and agricultural activities. Agriculture is concentrated mainly in the central part of the country, although it also occurs in northern

and southern regions under different environmental and productive conditions [28,35,36]. This diversity makes Chile an interesting case for investigating the relationship between agricultural development and changes in natural land cover. Agriculture has experienced important transformations over the last decades. In particular, the development of a commercially oriented agricultural sector has been accompanied by changes in agricultural production, productivity and land use [37] (Figure 1). At the same time, small-scale agriculture continues to represent an important component of the rural economy and is supported by different public programmes, particularly those implemented by the Instituto de Desarrollo Agropecuario (INDAP) [38,39]. Thus, commercial agriculture and publicly supported small-scale agriculture coexist within Chilean rural landscapes.



(**a**) (**b**)

Figure 1. Examples of rural landscapes in Chile: (**a**) commercial agricultural landscape; (**b**) natural land cover within a rural landscape. Photographs by the author.

The spatial distribution of land cover in Chile is illustrated in Figure 2 using the 2022 MapBiomas Chile classification. At the national scale (Figure 2a), agricultural and forestry land uses are unevenly distributed, with their greatest spatial concentration occurring in central and southern Chile. The closer view of this area (Figure 2b) reveals a heterogeneous landscape in which agriculture, forest plantations, pasture and natural land cover coexist. Agricultural areas are particularly evident around Santiago and further south, while forest plantations form extensive concentrations in the south-central part of the country. Pasture becomes increasingly prominent towards the southern portion of the mapped area, alongside substantial areas of natural vegetation. These spatial patterns illustrate that agricultural development takes place within landscapes characterised by competing and overlapping productive and environmental functions. They also provide geographical context for the empirical analysis, in which changes in commercially oriented agricultural land uses, agricultural output intensity and public support to small-scale producers are examined in relation to natural land cover. The map represents a cross-sectional description of land cover in 2022 and is not intended to establish the temporal relationships investigated econometrically.

In considering these characteristics, the empirical analysis covers the period 2000–2022. Annual data were obtained from different official sources and combined to construct a database describing changes in natural land cover, commercial agricultural area, agricultural productivity and public support for small-scale producers. Natural land-cover information was obtained from MapBiomas Chile [40], while agricultural and economic information was obtained from the Central Bank of Chile [41]. Information on public support was obtained from INDAP [42]. The selection of the period was determined by the availabil-

ity of comparable information for all variables. This produces an annual time series of 23 observations.

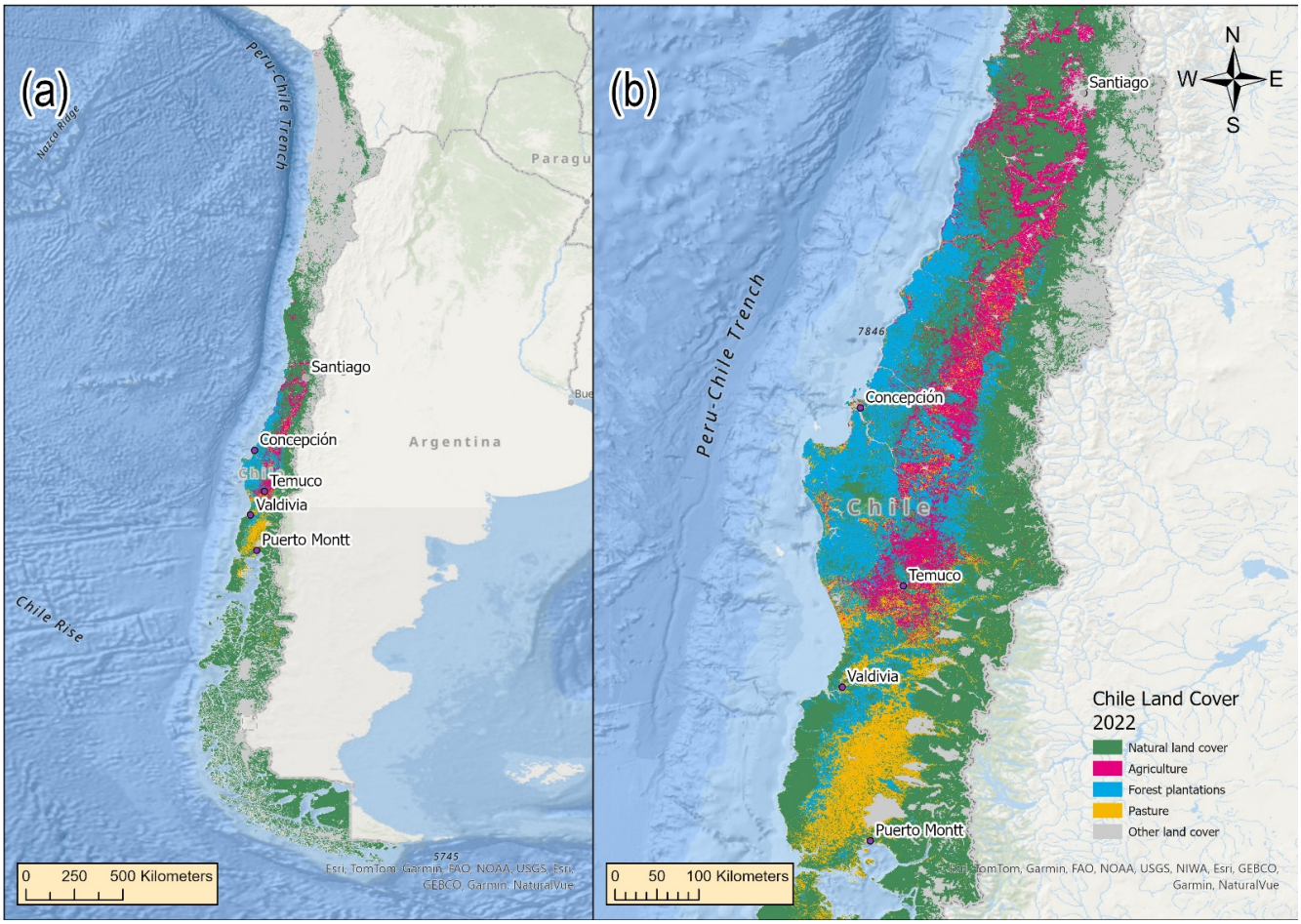

Figure 2. Spatial distribution of land cover in Chile in 2022: (**a**) national overview and (**b**) detailed view of central and southern Chile. Source: MapBiomas Chile, Collection 2 (2022). Map prepared by the author.

2.2. Variable Construction

Four variables are considered directly in the empirical analysis, with an additional land-use variable used in the construction of agricultural output intensity. The dependent variable, E_t, represents the proportion of natural land cover within the rural landscape and was reconstructed using the annual land-cover classifications provided by MapBiomas Chile Collection 2 [43]. MapBiomas Chile Collection 2 provides annual land-cover classifications derived from Landsat satellite imagery at a spatial resolution of 30 m, with a recommended cartographic scale of 1:100,000. The classifications are generated using Random Forest algorithms and spatial and temporal post-processing procedures. Although these methods seek to improve classification consistency, the resulting land-cover estimates remain subject to classification uncertainty, particularly for the earlier years of the series and for agricultural and forestry categories. These uncertainties should be considered when interpreting the land-cover variables constructed for this study.

Natural land cover ($Q_{natural,t}$) was calculated as the combined area classified as Primary Forest, Secondary Forest, Dwarf Forest, Wetland, Grassland, Steppe and Shrubland. Rural land ($Q_{rural,t}$) was defined as $Q_{natural,t}$ plus Agriculture, Forest Plantation, Pasture, Sand, Beach and Dune, Other Non-vegetated Area, Rocky Outcrop and Salt Flat. Infrastructure, water bodies, ice and snow, and unobserved areas were excluded from the rural-land denom-

inator. The dependent variable was then calculated as $E_t = Q_{natural,t}/Q_{rural,t}$, representing the proportion of the rural landscape covered by natural land-cover categories. The agricultural land variables were also constructed from the annual MapBiomas Chile Collection 2 classifications. Commercial agricultural area ($Q_{com,t}$) was defined as the combined area classified as Agriculture (class 18) and Forest Plantation (class 9), while pasture area ($Q_{pas,t}$) was represented by the area classified as Pasture (class 15). These categories are mutually exclusive land-cover classes within the broader MapBiomas Farming and Silviculture category (class 14), and their annual areas were measured in hectares. Importantly, the designation of commercial agricultural area ($Q_{com,t}$) is an operational classification constructed from MapBiomas land-cover categories rather than a direct producer-level classification. Agricultural land and forest plantations may be managed by producers of different scales, and these categories do not independently identify land managed by commercial enterprises. Pasture area ($Q_{pas,t}$), in turn, is included solely as an additional agricultural land-use category in the denominator of the agricultural output-intensity indicator. It is not used as a direct measure of land managed by small-scale producers. Thus, $Q_{com,t}$ captures the spatial extent of the selected commercially oriented agricultural and forestry land uses, while $Q_{pas,t}$ contributes to the agricultural land denominator used to calculate IN_t.

Because natural and agricultural land-cover classes are mutually exclusive components of the rural-land accounting system, part of the negative relationship between E_t and $Q_{com,t}$ is necessarily mechanical. A transfer of land from a natural-cover category to Agriculture or Forest Plantation simultaneously reduces the natural-cover numerator and increases commercial agricultural area. The coefficient on $Q_{com,t}$ should not be interpreted as an independent causal environmental effect of commercial agriculture. Rather, its empirical role is to capture how temporal changes in the allocation of rural land to commercial agricultural uses are associated with E_t within the multivariate long-run relationship, conditional on the other agricultural dimensions included in the model.

Agricultural development, however, cannot be represented only by changes in agricultural area. Production can also change without a corresponding expansion of agricultural land. To capture this second dimension, agricultural output intensity is measured as agricultural gross domestic product (AGDP) relative to total agricultural area. This approach is consistent with the use of agricultural value added per hectare as an indicator of land productivity in previous research, including the cross-country analysis reported by Goyal and Nash [44]. The indicator captures economic output per unit of agricultural land rather than total factor productivity and is calculated as follows:

$$IN_t = \frac{AGDP_t}{Q_{com,t} + Q_{pas,t}} \quad (1)$$

where $Q_{com,t}$ and $Q_{pas,t}$ represent the areas associated with commercial agriculture and pasture, respectively, both measured in hectares (ha). Agricultural GDP ($AGDP_t$) is measured in billions of Chilean pesos (CLP), using chain-linked volume measures with reference year 2018. Consequently, agricultural output intensity (IN_t) is expressed in CLP billion per hectare. Thus, while $Q_{com,t}$ captures changes in the spatial extent of commercial agriculture, IN_t captures changes in agricultural output relative to the land used for agricultural production. Finally, P_t represents public support directed towards small-scale agricultural producers through INDAP. The variable considers direct non-reimbursable support and excludes credit and expenditure associated with the internal administration of the institution. Agricultural GDP and INDAP support were expressed in real rather than nominal monetary units to avoid capturing common movements arising from inflation. Agricultural GDP was obtained from the Central Bank of Chile and is measured in billions of Chilean pesos (CLP) using chain-linked volume measures with reference year 2018. INDAP support was converted to real CLP billion with reference year 2018 using the gross fixed capital formation

(FBCF) deflator provided by the Central Bank of Chile. The FBCF deflator was selected because changes in the real value of the support variable are intended to reflect changes in the purchasing power of expenditure associated with the productive effects of INDAP programmes, for which an investment-related deflator provides a closer approximation than a general consumer-price index. Consequently, neither of the monetary series entering the empirical specification is expressed in nominal terms. This distinction is important because the purpose of P_t is not to measure the total size of INDAP, but the resources transferred to support productive activities undertaken by small producers. Table 1 summarises the variables, their construction and their respective sources.

Table 1. Variables used in the empirical analysis.

Variable	Description	Construction/Transformation	Units/Price Basis	Source
E_t	Natural land cover	$Q_{natural,t}/Q_{rural,t}$	Proportion (0–1)	MapBiomas Chile, Collection 2
$Q_{natural,t}$	Natural land-cover area	Primary Forest + Secondary Forest + Dwarf Forest + Wetland + Grassland + Steppe + Shrubland	ha	MapBiomas Chile, Collection 2
$Q_{rural,t}$	Rural land area	$Q_{natural}$ + Agriculture + Forest Plantation + Pasture + Sand, Beach and Dune + Other Non-vegetated Area + Rocky Outcrop + Salt Flat	ha	MapBiomas Chile, Collection 2
$Q_{com,t}$	Commercial agricultural area	Agriculture (class 18) + Forest Plantation (class 9)	ha	MapBiomas Chile, Collection 2
$Q_{pas,t}$	Pasture area	Pasture (class 15); included in the agricultural land denominator used to calculate IN_t	ha	MapBiomas Chile, Collection 2
$AGDP_t$	Agricultural and forestry GDP	Agricultural and forestry gross domestic product	CLP billion, chain-linked volume, reference 2018	Central Bank of Chile
IN_t	Agricultural output intensity	$AGDP_t/(Q_{com,t} + Q_{pas,t})$	CLP billion per ha	Constructed by the author
P_t	Public support to small-scale producers	Direct non-reimbursable INDAP support, excluding credit and expenditure associated with institutional administration; deflated using the FBCF deflator	Real CLP billion, reference 2018	INDAP; Central Bank of Chile

Note: FBCF denotes gross fixed capital formation. Commercial agricultural area is an operational land-use classification rather than a producer-level socioeconomic category supplied directly by MapBiomas. Pasture area is included in the construction of agricultural output intensity and is not interpreted as a direct measure of small-scale agricultural landholdings.

2.3. Econometric Approach

The empirical analysis examines whether natural land cover, commercial agricultural area, agricultural output per unit of agricultural land and public support to small-scale producers are linked through a long-run relationship. To specify this relationship empirically, the variables enter the model in the forms described in Section 2.2. Natural land cover (E_t) is expressed as the proportion of the rural landscape represented by natural land-cover categories. Commercial agricultural area ($Q_{com,t}$) is originally measured in hectares, while agricultural output intensity (IN_t) is calculated as real agricultural GDP per unit of agricultural land, expressed in CLP billion per hectare. Public support to small-scale producers (P_t) is expressed in real monetary terms (CLP billion). For numerical conditioning, $Q_{com,t}$ was divided by 10^6 and IN_t was multiplied by 10^6 before estimation, so that the former entered the estimated equations in millions of hectares and the latter in CLP billion per

million hectares. E_t and P_t were retained in their original units. These constant rescalings affect the numerical magnitude and units of the corresponding coefficients without altering the substantive specification or statistical inference. In addition, the revised specification allows the relationship between public support and natural land cover to be non-linear by including both P_t and P_t^2. This quadratic formulation was adopted because re-estimation using the corrected data indicated functional-form misspecification when the relationship with public support was restricted to be linear. The resulting long-run specification is therefore:

$$E_t = \beta_0 + \beta_1 Q_{com,t} + \beta_2 IN_t + \beta_3 P_t + \beta_4 P_t^2 + u_t \quad (2)$$

where E_t represents the proportion of natural land cover within the rural landscape, $Q_{com,t}$ is commercial agricultural area, IN_t denotes agricultural output intensity, and P_t represents public support to small-scale agricultural producers. The intercept is denoted by β_0, while β_1 and β_2 are the coefficients associated with commercial agricultural area and agricultural output intensity, respectively. The coefficients β_3 and β_4 capture the linear and quadratic components of the relationship between public support and natural land cover. Finally, u_t represents deviations from the estimated long-run relationship. However, estimating this relationship directly without considering the time-series properties of the variables may produce spurious results. For this reason, Augmented Dickey–Fuller (ADF) and Kwiatkowski–Phillips–Schmidt–Shin (KPSS) tests are first applied to examine the stationarity properties of the variables in levels and first differences. The two tests are considered jointly because they have opposite null hypotheses: the ADF test considers the presence of a unit root as its null hypothesis, whereas the KPSS test considers stationarity as its null hypothesis. Both tests include an intercept but no deterministic trend. For the ADF tests, augmentation lags are selected separately for each variable and transformation by minimising the Bayesian information criterion (BIC) over candidate lag orders from zero to two. To ensure comparability across candidate specifications, the BIC is calculated over a common effective sample determined by the maximum candidate lag. For the KPSS tests, the long-run variance is estimated using four Newey–West autocovariance lags. Sensitivity to this choice is examined using lag truncations from zero to four. All tests are evaluated at the 5% significance level. The inclusion of the quadratic term in public support requires a cointegration approach that accommodates polynomial transformations of integrated regressors. The long-run relationship is estimated as a cointegrating polynomial regression (CPR) using fully modified OLS (FM-OLS), following the methodology developed by Wagner and Hong [45]. This estimator is designed for polynomial cointegrating relationships and accounts for serial correlation and endogeneity in the long-run regression.

Cointegration is assessed using the complementary residual-based tests developed for cointegrating polynomial regressions by Wagner [46]. The CT test considers cointegration as the null hypothesis, whereas the PU test considers no cointegration as the null hypothesis. Considering the two tests jointly is useful because they approach the existence of a polynomial cointegrating relationship from opposite null hypotheses. Evidence in favour of cointegration is strongest when the CT null is not rejected, and the PU null is rejected. Conversely, rejection of the CT null combined with non-rejection of the PU null provides evidence against cointegration. Other combinations are treated as inconclusive rather than as establishing the presence or absence of cointegration. The tests are implemented using a Bartlett kernel and the automatic Newey–West bandwidth selection procedure. The relatively short annual sample is an important limitation of the analysis. Only 23 annual observations are available, which reduces the power of cointegration tests and the precision with which the long-run coefficients can be estimated. It also requires particular caution in interpreting procedures whose critical values rely on asymptotic approximations. For this reason, the analysis does not rely on a multivariate system-based procedure such as the

Johansen approach. Instead, the long-run relationship is estimated using FM-CPR, which directly accommodates the polynomial structure of the specification, and cointegration is assessed using the complementary CT and PU residual-based tests developed specifically for cointegrating polynomial regressions. The use of these methods addresses the polynomial structure of the model but does not eliminate the finite-sample limitations associated with the short time series. Therefore, the CT and PU tests are considered jointly, and combinations in which the two tests do not provide mutually reinforcing evidence are treated as inconclusive rather than as establishing cointegration. The estimated long-run coefficients are likewise interpreted as conditional associations within the estimated relationship rather than as precisely identified structural effects.

To complement the long-run analysis, short-run dynamics are examined using an error correction model (ECM). The error-correction term is constructed from the lagged residual of the FM-CPR long-run relationship in Equation (2), thereby linking short-run changes in natural land cover to deviations from the estimated polynomial long-run relationship. To preserve the quadratic specification of public support in the short-run dynamics, changes in both P_t and P_t^2 are included. The ECM is specified as:

$$\Delta E_t = \alpha_0 + \alpha_1 \Delta Q_{com,t} + \alpha_2 \Delta IN_t + \alpha_3 \Delta P_t + \alpha_4 \Delta P_t^2 + \lambda ECT_{t-1} + u_t \quad (3)$$

where ECT_{t-1} is the lagged residual from the FM-CPR long-run relationship. The coefficient λ measures adjustment following a deviation from that relationship. A negative coefficient with an adjustment root $1 + \lambda$ lying inside the unit circle is consistent with convergence towards the estimated long-run relationship. Given the small effective sample available for the ECM, heteroskedasticity-consistent HC3 standard errors are also reported alongside conventional standard errors. Model adequacy is assessed using Breusch–Godfrey tests for residual serial correlation, the Breusch–Pagan test for heteroskedasticity, the Jarque–Bera test for residual normality, and the Ramsey RESET test for functional-form misspecification. Parameter stability is additionally examined using the recursive-residual CUSUM test, while dynamic stability is assessed from the adjustment root $1 + \lambda$. Given the small sample, these diagnostics are interpreted cautiously, particularly the recursive stability test. For the FM-CPR equation, supplementary residual diagnostics are also examined for serial correlation, heteroskedasticity and normality; because the long-run equation is a cointegrating polynomial regression rather than a stationary OLS model, these are treated as descriptive residual diagnostics rather than conventional OLS specification tests.

Given the limited number of annual observations, the ECM was specified parsimoniously, without undertaking a formal lag-order selection procedure, to limit the number of estimated parameters and preserve degrees of freedom. The adequacy of this specification is examined through residual diagnostic tests and parameter stability assessments reported in Section 3. Nevertheless, these procedures do not establish that the chosen lag structure is optimal, and sensitivity to alternative dynamic specifications remains a limitation of the analysis.

The econometric analysis and diagnostic procedures were implemented using MATLAB Online (R2026b, Update 1; MathWorks). Generative artificial intelligence (ChatGPT, OpenAI, including GPT-6) was used to assist with the organisation and refinement of the manuscript and the interpretation and presentation of econometric results. All methodological decisions, data construction, statistical analyses, verification of results and final interpretations remained the responsibility of the author.

3. Results

Figure 3 presents the annual evolution of natural land cover, commercial agricultural area, agricultural output intensity and public support to small-scale producers in Chile

between 2000 and 2022. These descriptive trends provide context for the subsequent econometric analysis.

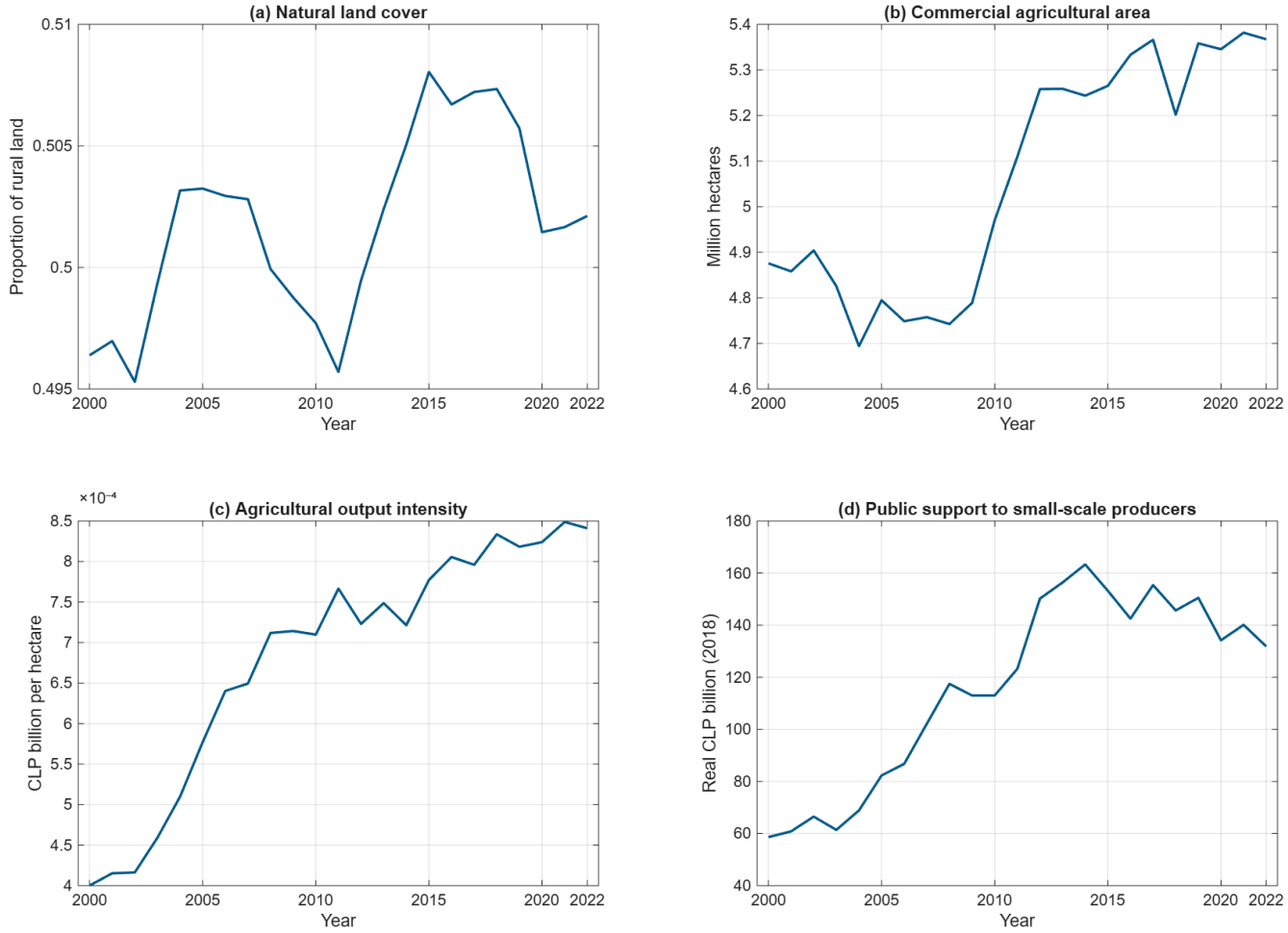

Figure 3. Temporal evolution of natural land cover, commercial agricultural area, agricultural output intensity and public support to small-scale producers in Chile, 2000–2022.

Figure 3 reveals distinct temporal patterns across the four variables. Natural land cover remained relatively stable over the study period, although it exhibited noticeable fluctuations, including a decline around 2011, a subsequent recovery until approximately 2015, and a further reduction towards 2020. In contrast, commercial agricultural area increased overall, particularly from the late 2000s onwards, despite intermittent declines. Agricultural output intensity followed a broadly upward trajectory, approximately doubling between 2000 and 2022, suggesting an increase in agricultural output per unit of land. Public support for small-scale producers also increased substantially during the first part of the period, reaching its highest levels in the mid-2010s, before fluctuating and declining towards 2022. Taken together, these descriptive patterns indicate that agricultural expansion, output intensity and public support evolved differently from natural land cover, highlighting the importance of examining their relationships through the subsequent econometric analysis.

3.1. Time-Series Properties and Long-Run Relationship

Before examining the long-run relationship between agriculture and natural land cover, the time-series properties of the variables were investigated. Table 2 presents the results of the Augmented Dickey–Fuller (ADF) and KPSS tests in levels and first differences.

Table 2. Unit-root tests for variables used in the empirical analysis.

Variable	Transformation	ADF Lag	ADF Statistic	5% CV	*p*-Value	KPSS Lag	KPSS Statistic	5% CV	*p*-Value
E_t	Level	1	−2.3142	−3.0141	0.1771	4	0.3167	0.4630	0.1000
ΔE_t	First difference	0	−3.1537	−3.0141	0.0380	4	0.1079	0.4630	0.1000
$Q_{com,t}$	Level	0	−0.4961	−3.0067	0.8741	4	0.4841	0.4630	0.0453
$\Delta Q_{com,t}$	First difference	0	−4.4114	−3.0141	0.0034	4	0.1361	0.4630	0.1000
IN_t	Level	1	−2.4377	−3.0141	0.1446	4	0.5357	0.4630	0.0336
ΔIN_t	First difference	0	−5.1484	−3.0141	0.0010	4	0.2982	0.4630	0.1000
P_t	Level	0	−1.6449	−3.0067	0.4465	4	0.4797	0.4630	0.0462
ΔP_t	First difference	0	−4.1234	−3.0141	0.0049	4	0.3183	0.4630	0.1000

The ADF tests do not reject the unit-root null for any of the four variables in levels. The KPSS tests complement this evidence for commercial agricultural area, agricultural output intensity and public support by rejecting level stationarity. For natural land cover, however, the KPSS result in levels is sensitive to the choice of autocovariance lag: stationarity is rejected with zero or one lag but not with two to four lags. The evidence for this variable in levels is less clear-cut. After first differencing, the ADF tests reject the unit-root null for all four variables, while the KPSS tests do not reject stationarity. These first-difference results are also robust across the alternative KPSS lag truncations considered. Overall, the results provide clear evidence consistent with I(1) behaviour for commercial agricultural area, agricultural output intensity and public support, while the evidence for natural land cover is less decisive in levels, but its first difference is stationary under both tests. This provides the basis for examining the polynomial long-run relationship, while recognising the uncertainty concerning the precise integration properties of natural land cover. The FM-CPR estimates of the long-run relationship are presented in Table 3. Public support enters both linearly and quadratically, as specified in Equation (2).

Table 3. FM-CPR estimates of the long-run relationship.

Variable	Coefficient	SE	*t*-Statistic	*p*-Value
Constant	0.595900	0.024703	24.123	<0.001
$Q_{com,t}$	−0.015069	0.004121	−3.657	<0.001
IN_t	0.00005686	0.00001483	3.835	<0.001
P_t	−0.001099	0.000278	−3.954	<0.001
P_t^2	0.000004815	0.000001114	4.323	<0.001

Notes: Two-sided asymptotic *p*-values are based on the standard normal distribution.

The estimated coefficients indicate distinct long-run associations across the three dimensions of agricultural development. Commercial agricultural area has a negative coefficient, whereas agricultural output intensity has a positive coefficient. Conditional on the other variables in the relationship, increases in commercial agricultural area are associated with a lower proportion of natural land cover, while greater agricultural output per unit of agricultural land is associated with a higher proportion of natural cover. As discussed in Section 2.2, the coefficient on commercial agricultural area must be interpreted partly in light of the accounting relationship between agricultural and natural land-cover categories and should not be interpreted as an independently identified causal effect. The relationship with public support is non-linear. The coefficient on P_t is negative and that on P_t^2 is positive, implying a U-shaped estimated relationship conditional on the other variables. The corresponding turning point is calculated using the linear and quadratic

coefficients of public support: $P^* = -\frac{\beta_P}{2\beta_{P2}} = \frac{0.0010994}{2x0.0000048146} \approx 114.17$. The estimated turning point is therefore approximately 114.17 billion Chilean pesos (CLP), expressed in real terms with reference to 2018. This value lies within the observed range of public support (58.64–163.32 real CLP billion). The small difference obtained when using the rounded coefficients displayed in Table 3 is attributable to rounding. Thus, within the estimated relationship, increases in public support are associated with lower natural land cover below the turning point, whereas the estimated marginal association becomes positive above it. This non-linearity is important because the relationship between public support and natural land cover cannot be represented by a single negative coefficient over the entire observed range. Statistical significance of the individual FM-CPR coefficients does not, however, establish that the variables form a cointegrating relationship. The complementary CT and PU tests were applied to the residuals of the estimated polynomial relationship. The results are reported in Table 4.

Table 4. Residual-based tests for cointegrating polynomial regression.

Test	Null Hypothesis	Statistic	5% Critical Value	Decision
CT	Cointegration	0.060934	0.145740	Do not reject
PU	No cointegration	3.948360	50.916442	Do not reject

Notes: CT and PU are the complementary residual-based tests for cointegrating polynomial regressions developed by Wagner [46]. Tests use a Bartlett kernel and Newey–West bandwidth selection.

The CT test does not reject its null hypothesis of cointegration, but the PU test also does not reject its null hypothesis of no cointegration. The two tests do not provide the mutually reinforcing pattern required to establish cointegration. The evidence is compatible with cointegration but remains inconclusive. This ambiguity is particularly relevant given the short annual sample and the associated limitations on test power discussed in Section 2.3. Accordingly, the estimated FM-CPR coefficients are interpreted below as conditional long-run associations rather than as definitive evidence of a stable equilibrium relationship. Supplementary examination of the FM-CPR residuals does not indicate heteroskedasticity or non-normality. The residual serial-correlation diagnostics are less uniform: the first-order auxiliary LM statistic is significant at the 5% level, whereas the second-order diagnostic is not. These residual checks are interpreted descriptively because conventional OLS diagnostic distributions do not directly carry over to the cointegrating polynomial regression setting.

Graphical inspection of the FM-CPR residuals (Figure 4a) and leave-one-year-out re-estimation were additionally used to assess sensitivity to individual annual observations. The largest absolute FM-CPR residual occurred in 2005, followed closely by the negative residual in 2011. Nevertheless, the FM-CPR estimates were robust to individual-year exclusion. All coefficients retained their full-sample signs across all 23 re-estimations and remained statistically significant using asymptotic inference. In particular, the estimated relationship with public support remained U-shaped in every re-estimation, with the turning point ranging from 112.32 to 116.42 and remaining within the observed support range in all cases.

3.2. Short-Run Dynamics and Adjustment

Given the inconclusive cointegration evidence, the ECM is used as a conditional analysis of short-run dynamics around the estimated FM-CPR relationship rather than as independent confirmation that cointegration has been established. The error-correction term is constructed from the lagged residual of the FM-CPR relationship in Equation (2), while changes in both public support and its squared term are retained to preserve the polynomial specification. The estimation results are presented in Table 5.



Figure 4. Residuals from the long-run and short-run specifications. (**a**) FM-CPR residuals from the estimated long-run relationship; (**b**) residuals from the error-correction model. The dashed horizontal line indicates zero.

Table 5. Error correction model estimates.

Variable	Coefficient	Conventional SE	Conventional p	HC3 SE	HC3 p
Constant	0.0002363	0.0005141	0.6520	0.0005767	0.6874
$\Delta Q_{com,t}$	-1.4197×10^{-8}	5.029×10^{-9}	0.0122	5.816×10^{-9}	0.0266
ΔIN_t	22.0529	16.723	0.2058	26.327	0.4146
ΔP_t	−0.0003193	0.0002182	0.1629	0.0002776	0.2670
ΔP_t^2	1.5962×10^{-6}	8.451×10^{-7}	0.0772	1.098×10^{-6}	0.1652
ECT_{t-1}	−0.534328	0.1906	0.0127	0.2528	0.0506

The coefficient on the lagged error-correction term is negative ($\lambda = -0.5343$). Under conventional inference, it is statistically significant ($P = 0.0127$), while the HC3 p-value is 0.0506, lying just above the conventional 5% threshold. The estimated coefficient is consistent with adjustment towards the FM-CPR relationship, although the evidence becomes borderline once inference is made robust to heteroskedasticity in the small effective sample.

Its magnitude implies that approximately 53% of an estimated deviation is corrected in the following year. The corresponding adjustment root is $1 + \lambda = 0.4657$, which lies between zero and one and implies monotonic rather than oscillatory adjustment. Among the short-run agricultural variables, changes in commercial agricultural area have a negative coefficient and remain statistically significant using HC3 inference ($P = 0.0266$). Changes in agricultural output intensity are not statistically significant ($P_{HC3} = 0.4146$). The coefficients on changes in public support and its squared term are also individually insignificant using HC3 inference ($P_{HC3} = 0.2670$ and 0.1652, respectively). Consequently, the short-run results do not provide evidence of a statistically significant public-support effect when the quadratic specification and HC3 inference are taken into account. Because public support enters quadratically, its short-run association would in any case depend jointly on the coefficients of ΔP_t and ΔP_t^2, rather than on either coefficient considered in isolation.

The ECM explains approximately 53.9% of the variation in annual changes in natural land cover ($R^2 = 0.539$; adjusted $R^2 = 0.395$). The diagnostic and stability test results for the error-correction model are presented in Table 6. Diagnostic tests provide no evidence of heteroskedasticity (Breusch–Pagan $P = 0.184$) or functional-form misspecification (RESET $P = 0.292$). The Breusch–Godfrey tests do not reject the null hypothesis of no serial correlation at the 5% level, although the results for one and two lags ($P = 0.094$ and $P = 0.077$, respectively) warrant some caution. The Jarque–Bera test likewise does not reject normality ($P \geq 0.50$). Taken together, these diagnostics do not indicate major residual problems, although their power is necessarily limited by the small sample. Inspection of the ECM residuals (Figure 4b) and influence diagnostics identified several potentially influential annual observations, but no single year determined the estimated adjustment dynamics. In leave-one-year-out estimations, the error-correction coefficient remained negative in every case, ranging from −0.667 to −0.411, while the corresponding adjustment root remained between 0.333 and 0.589. The qualitative conclusion of stable, monotonic adjustment was preserved across all individual-year exclusions.

Table 6. Diagnostic and stability tests for the error-correction model.

Diagnostic	Statistic	*p*-Value/Result
Breusch–Godfrey LM(1)	2.8044	0.0940
Breusch–Godfrey LM(2)	5.1320	0.0768
Breusch–Pagan	7.5343	0.1838
Jarque–Bera	0.5750	≥0.500
Ramsey RESET	1.3475	0.2916
CUSUM	—	No 5% boundary crossing
Adjustment root $1 + \lambda$	0.4657	Stable, monotonic adjustment

4. Discussion

The results identify an estimated long-run relationship between agricultural development and natural land cover in Chile, although the complementary cointegration tests do not provide mutually confirming evidence that this relationship is cointegrating. The long-run coefficients should be interpreted as conditional associations within the estimated FM-CPR relationship rather than as evidence of an established long-run equilibrium. The estimated coefficients nevertheless provide evidence of systematic associations between natural land cover and the three dimensions of agricultural development considered here. These associations differ considerably across commercial agricultural area, agricultural output per unit of agricultural land and support to small-scale producers.

This suggests that the consequences for natural land cover depend not only on changes in agricultural production, but also on how this production is achieved and supported. Commercial agricultural area is negatively associated with natural land cover. This result must, however, be interpreted in light of the accounting relationship between the two variables. Because commercial agricultural and natural land-cover categories are mutually exclusive components of the rural landscape, part of their negative association is inherent in their construction: land classified as Agriculture or Forest Plantation cannot simultaneously be classified as natural cover. The estimated coefficient should not be interpreted as independently identifying an environmental effect of commercial agricultural expansion. Its contribution is instead to characterise the temporal land-allocation component of the estimated FM-CPR relationship, conditional on agricultural output intensity and public support. At the same time, this accounting relationship represents a substantive land-use constraint. An expansion of commercial agriculture requires additional land and can take place at the expense of forests, shrublands and other natural covers. Previous studies have similarly shown that agricultural expansion can contribute to the transformation of natural and cultural landscapes [4,20]. The estimated negative association is consistent with competition for rural land between agricultural and natural uses, while its direction must be interpreted partly in the context of the underlying land-cover accounting structure.

Agricultural output per unit of agricultural land presents a different relationship. Its positive coefficient in the FM-CPR specification is consistent with the possibility that increases in agricultural production do not necessarily require an equivalent expansion of agricultural land. One possible explanation is that greater production from land already under agricultural use reduces the need to incorporate additional land. This would be consistent with a land-sparing mechanism [20]. However, this result should not be interpreted as evidence that agricultural intensification is necessarily environmentally beneficial. Agricultural production can generate environmental pressures other than changes in land cover, and these are not captured by E_t. Moreover, its short-run coefficient is not statistically significant under HC3 inference. Nevertheless, the different signs obtained for commercial agricultural area and agricultural output per unit of land indicate that increasing production through the expansion of agricultural land and increasing production from land already in use can have different relationships with natural cover.

The estimated relationship between public support to small-scale producers and natural land cover is particularly relevant in this context. In the FM-CPR specification, this relationship is U-shaped, with increases in public support associated with lower natural land cover below the estimated turning point and with higher natural land cover above it. The estimated turning point occurs at a public-support level of approximately 114.17, which lies within the observed range of the variable. This result should not be interpreted as evidence that public support independently determines natural land cover. The estimated coefficients characterise the conditional association of public support within the multivariate long-run relationship, and neither the cointegration analysis nor the individual coefficients establish a causal effect. This distinction is particularly important because reverse causality cannot be excluded: changes in natural land cover or associated environmental conditions may themselves influence agricultural policy decisions and the allocation of public support. Moreover, omitted factors, including climatic variability, regulatory changes and broader agricultural policies, may affect both public support and land use, potentially influencing the estimated associations. At the same time, the estimated association remains relevant to the broader policy context: small-scale agriculture can contribute to maintaining rural traditions and cultural landscapes [1,23], while policies directed towards small producers are also intended to strengthen their productive activities [42]. These different objectives need not imply the same relationship with natural land cover.

Several mechanisms could potentially be consistent with this estimated non-linear association, although the present analysis cannot identify or distinguish among them. One possible explanation is that the marginal productive effect of public support varies with its level. When support is relatively low, additional assistance may relax important financial and capital constraints faced by small-scale producers, facilitating the adoption of productive technologies and generating comparatively large increases in productive capacity [31]. Under these conditions, additional support may increase pressure on natural land cover, particularly where productivity gains increase the profitability of agricultural production and create incentives for agricultural expansion [30]. As support increases, however, the marginal productive response to additional assistance may decline [32], reducing this source of pressure on natural land cover. At higher levels of support, additional resources may also facilitate forms of investment or land management that increase production without requiring a corresponding expansion of commercial agricultural land, while the environmental consequences of agricultural support may depend on the form and conditions under which support is provided [33,34], and environmental policy interventions may also generate indirect land-use effects [47]. These mechanisms could contribute to a change in the direction of the association between public support and natural land cover as the level of support increases. However, the present analysis does not identify how the use or composition of public support changes with its level, and these mechanisms should be regarded as possible explanations of the estimated U-shaped relationship rather than as causal processes established by the results.

The distinction between the short- and long-run estimates is particularly important for this result. In the FM-CPR specification, the association between public support and natural land cover is non-linear rather than uniformly negative, with the estimated quadratic relationship changing direction within the observed range of public support. In the ECM, by contrast, the coefficients on changes in public support and its squared term are individually insignificant under HC3 inference. The results therefore do not provide evidence of a statistically significant short-run public-support effect.

The error-correction results provide additional, although qualified, information about short-run adjustment around the estimated FM-CPR relationship. The coefficient on the lagged error-correction term is negative, and its estimated adjustment root lies between zero and one, implying monotonic rather than oscillatory adjustment. However, its statistical significance becomes borderline under HC3 inference. Given both this result and the inconclusive cointegration tests, the ECM should be interpreted as conditional evidence concerning adjustment around the estimated long-run relationship rather than as independent confirmation of a stable long-run equilibrium. These results have implications for the way in which agricultural support is considered within rural development policy. Supporting small-scale agriculture can contribute to economic and social objectives, including the maintenance of rural livelihoods and agricultural activities. However, these benefits do not necessarily imply that environmental objectives will move in the same direction. If productive support contributes to maintaining or increasing the productive use of agricultural land, policies that are successful according to their primary objectives may also have unintended consequences for natural land cover. This does not imply that support to small-scale producers should be reduced. Rather, productive and social objectives could be considered together with complementary measures addressing their possible environmental consequences. For example, support aimed at improving agricultural production could be accompanied by incentives encouraging the protection of natural vegetation or favouring increases in production that do not require additional agricultural land.

More generally, the results suggest that the relationship between agricultural development and natural land cover cannot be reduced to a simple distinction between commercial

and small-scale agriculture. Commercial agricultural expansion is negatively associated with natural land cover, whereas the estimated relationship with support directed towards small-scale producers is non-linear and changes direction within the observed range of support. Agricultural output per unit of land, in contrast, presents a positive association with natural land cover. The relationship between agricultural development and natural land cover may depend not only on the type of agricultural activity, but also on whether changes in production occur through spatial expansion or through greater output from agricultural land already in use, and on the policy context within which these changes occur.

Limitations

The analysis is subject to several limitations. First, the availability of only 23 annual observations restricts the statistical power of the unit-root and cointegration tests, reduces the precision of the estimated relationships, and limits the reliability of asymptotic inference. These limitations are particularly relevant to the inconclusive evidence from the complementary CT and PU cointegration tests and the borderline statistical significance of the error-correction coefficient under HC3 inference. In particular, the HC3 p-value of 0.0506 lies marginally above the 5% significance threshold, meaning that the evidence of error correction is sensitive to the choice of standard errors and should not be regarded as statistically significant at the 5% level under robust inference. The restricted sample also limits the complexity of the dynamic specification that can be estimated reliably. Although the analysis incorporates residual diagnostic tests, parameter stability assessments and leave-one-year-out estimations, these procedures cannot fully overcome the uncertainty associated with the small sample. The results should therefore be interpreted as indicative conditional associations rather than definitive evidence of a stable long-run equilibrium or causal relationships.

Furthermore, the national aggregation of the data may conceal important regional differences in agricultural systems, climatic conditions and land-use dynamics, while potentially relevant influences not included in the model may affect the estimated associations. Evidence from spatially focused studies in other countries also illustrates how agricultural land-use transformations are shaped by local environmental and socioeconomic conditions [48]. Consequently, the national associations estimated here should not be assumed to apply uniformly across Chilean regions or to other geographical contexts. This concern is supported by evidence from Chile, where Peña-Cortés et al. [36] identify substantial geographical heterogeneity in rural territories, distinguishing 34 territorial typologies across six macrozones with different productive and environmental characteristics. These findings reinforce the importance of spatial context and suggest that the national associations estimated in this study should not be assumed to apply uniformly across Chilean regions or other geographical settings.

5. Conclusions

Agriculture plays an important role in rural development, but changes in agricultural production can also affect the landscapes where this activity takes place. This article investigated this relationship in Chile by considering three different dimensions of agricultural development: commercial agricultural area, agricultural output per unit of agricultural land, and public support to small-scale producers. The FM-CPR analysis identifies systematic associations between natural land cover and the three dimensions of agricultural development considered here. As the complementary cointegration tests are inconclusive, these estimates are interpreted as conditional associations rather than as evidence of an established long-run equilibrium. The nature of this relationship differs across the three

agricultural dimensions. Commercial agricultural area is negatively associated with natural land cover, which is consistent with competition for land between agricultural and natural uses. Agricultural output per unit of agricultural land, on the other hand, presents a positive relationship with natural cover. This suggests that increases in agricultural production do not necessarily need to be accompanied by an equivalent expansion of agricultural land. Finally, the estimated association between public support and natural cover is non-linear in the FM-CPR specification, while the short-run ECM provides no statistically significant evidence of a public-support effect under HC3 inference.

The latter result is particularly relevant because small-scale agriculture is frequently associated with traditional rural landscapes and practices. However, policies supporting small producers are also intended to maintain and strengthen agricultural activities. Their economic and social benefits do not necessarily imply positive effects on natural land cover. Productive support may contribute to maintaining land under agricultural use that otherwise could be abandoned or may facilitate changes in the use of productive land. The present analysis cannot identify which of these mechanisms explains the estimated relationship. Nonetheless, the estimated association suggests that public support and natural land cover should not necessarily be considered as independent dimensions of rural development. This does not imply that support to small-scale producers should be reduced. Rather, the results suggest that productive, social and environmental objectives should be considered jointly when agricultural support policies are designed and evaluated. In particular, policies aimed at strengthening small-scale agriculture may benefit from considering their possible consequences for land use alongside their economic and social objectives.

The contribution of this study lies in examining these three dimensions of agricultural development within a common empirical framework. Whereas previous research has investigated the environmental consequences of agricultural expansion and intensification, the role of traditional agriculture in rural landscapes, and the productive and social outcomes of agricultural support policies, these strands of research have generally been considered separately. By bringing commercial agricultural area, agricultural output intensity and public support to small-scale producers into the same analysis, this study provides evidence on how their respective associations with natural land cover may differ. In particular, the estimated non-linear relationship involving public support highlights an environmental dimension of agricultural policy that may be overlooked when its outcomes are assessed primarily in productive or social terms.

Some limitations should be considered when interpreting these results. With only 23 annual observations, the statistical reliability of the estimated relationships remains constrained, particularly given the limited power of cointegration tests and the reliance of FM-CPR inference on asymptotic approximations. Although the leave-one-year-out sensitivity analysis indicates that the principal coefficient signs are relatively stable, this does not eliminate uncertainty concerning the underlying long-run relationship or the robustness of statistical inference in such a small sample. Moreover, the estimated relationships do not establish causality, and the national scale of the analysis may conceal important regional differences in agricultural systems, environmental conditions and patterns of public support. Future research could examine these relationships at the regional level and investigate more directly the mechanisms through which agricultural support is associated with changes in natural land cover. This would be particularly useful for identifying whether the observed relationship operates through the maintenance of existing agricultural land, changes in agricultural abandonment, expansion into natural areas, or other land-use processes.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/world7110194/s1, File S1: Annual dataset for Chile (2000–2022),

including variable definitions, data sources and transformations used in the econometric analysis (world-4622099-supplementary.xlsx). The dataset was compiled using information from MapBiomas Chile [40], the Central Bank of Chile [41] and INDAP [42].

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