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Abstract

This paper questions the role of land property rights in coping with heat damage in agriculture. Taking advantage of a staggered cadastral reform that occurred in Greece between 2011 and 2019, we show that farmers having received the reform virtually offset all of the detrimental effects of abnormal heat exposure on crop yields. This pattern is consistent with our results indicating that farmers receiving better land property rights switch from land-extensification (i.e., adjustment of farmland area) to land-intensification strategies (i.e., adjustment of other inputs), ultimately reducing heat damage on crop yields. Our preferred estimates indicate that farmers receiving better land property rights reduce crop area expansion by at least seventy percent in face of abnormal heat exposure (compared to a no-reform situation). At the same time, they increase their utilization of machinery by point one percent respectively – while they reduce it by one percent when they do not receive the reform. These results underline the detrimental role of institutions in encouraging our societies to adapt to climate change.

Keywords: adaptation incentives, agriculture, institutional quality, land tenure, land regulation, weather shocks.

JEL Codes: P14, Q15, Q54

1 Introduction

Hundreds of studies have consistently documented the large detrimental effects of heat on crop yields all around the world (Schlenker and Roberts, 2009; Lobell et al., 2011, 2013; Asseng et al., 2015; Burke and Emerick, 2016; Gammans et al., 2017; Wing et al., 2021). While the first bunch of studies aimed at quantifying the extent of crop yield reduction (see Blanc and Schlenker, 2017, for a literature review), more recent ones have turned towards the analysis of the implementation of proper adaptation strategies (Aragón et al., 2021; Jagnani et al., 2021; Bareille and Chakir, 2024). Together, these analyses clearly indicate that greater exposure to heat not only reduces crop yields (once temperature exceeds 30°C or so), but also encourages farmers to modify their cropping practices and areas (hereinafter referred to as "adaptation at the intensive margin" and "adaptation at the extensive margin" respectively). However, the direction and magnitude of these adaptation behaviors remain the subject of contentious debate. For example, Cui (2020) and Ji and Cobourn (2021) documented that US farmers reduce cropland area in response to greater heat exposure, while Aragón et al. (2021) and Amare and Balana (2023) respectively indicated that Peruvian and Nigerian farmers respond to similar shocks by expanding theirs. Similarly, Burke and Emerick (2016) underlined that US farmers do not adjust their use of fertilizers in response to greater heat exposure, while Chen and Gong (2021) and Amare and Balana (2023) respectively showed that Chinese and Nigerian farmers respond to similar shocks by reducing fertilizer applications. We explain below that these apparently conflicting results across studies are actually consistent with the – so far ignored – role of land property rights in changing the picture.

This paper formally examines how the quality of land property rights affects the extent of heat damage on agriculture by shaping farmers' incentives to adapt. For this purpose, we take advantage of a natural experiment that recently occurred in Greece to assess the impacts of heat on (i) farmers' adaptation strategies and (ii) related crop yield losses in function of (iii) the quality of their land property rights. Known as the "Hellenic Cadastre", this program has set up a new land tenure system equipped with cadastral maps and digitally delimited boundaries for most Greek regions in a staggered way since 2008. We combine the information on the timing of the cadastral reform with data on annual weather and regional agricultural statistics to create a balanced panel of 59 regions between 2011 and 2019.

To assess the role of the cadastral reform in modifying the impacts of heat on crop yields and farmers' adaptation strategies, our identification strategy compares (i) the effects of region-specific abnormal deviations in annual heat exposure on our variable of interests between (ii) the regions that have received the reform and (iii) those who have not (or not already). Our research design thus exploits within-sample variations related to (i) a continuous variable measuring annual heat exposure in number of days above 30°C during the growing season – between April 1 and August 31 in Greece – and (ii) a dummy variable taking the value one if the region has received the reform at least two years ago – and zero otherwise – in order to identify their impacts on (iii) yields of the three major crops in Greece (wheat, barley and maize, which together occupy more than eighty percent of the Greek arable area), (iv) farmers' adaptation strategies at the extensive margin (areas allocated to each of the three major crops), and (v) farmers' adaptation strategies at the intensive margin (quantity of fertilizers, irrigation and machinery per hectare). Our preferred specification specifically establishes a relationship between our outcomes of interest and our two treatment variables *independently* and *in interaction*, conditionally on various controls and region fixed effects. To assess the effect of the quality of land property rights in affecting the heat impacts on crop yields and farmers' adaptation strategies, we pay a specific attention to the estimated value of the interaction between the two treatments.

Our results indicate that farmers having received the cadastral reform offset at least twenty-five, twelve and fifty-six percent of the negative effects of abnormal heat exposure on wheat, barley and maize yields respectively (compared to a situation where they would have not received the reform). These heat damage reductions are consistent with our complementary evidence showing that farmers having received the reform switch from land-extensification (i.e., adjustment of farmland areas) to land-intensification strategies (i.e., adjustment of other inputs). Specifically, our preferred estimates indicate that, compared to a situation where they would have not (yet) received the reform, farmers having experienced the reform restrain the expansion of their cropping areas by at least seventy percent at the average point. These same farmers increase their utilization of machinery by a tenth of a percent in response to an additional day of exposure above 30°C, while those who did not receive the reform reduce their utilization of machinery by one percent for a similar shock.

Our work contributes to three bodies of literature. We first contribute to the extensive literature measuring the detrimental effects of heat on crop yields (see also Carter et al., 2018, for an alternative review), by showing that the extent of the heat damage depend on the quality of the land property rights entitled to the farmers. While our results indicate that heat unambiguously reduces crop yields when Greek farmers conserve their initially incomplete land property rights, they show that farmers who have received the cadastral reform can virtually offset all of these detrimental effects. These results indicate a clear role for institutions in encouraging our societies to adapt to climate change – see Bezabih et al. (2021) or Henry (2022) for related research with alternative methods in the context of agriculture. They particularly stress the importance of the quality of land institutions in shaping the incentives to farmers to adapt to climate change.

Second, we contribute to the narrower literature measuring farmers' adaptation strategies to climate change (Kawasaki, 2019; Jagnani et al., 2021; Cui and Xie, 2022). We particularly shed new lights on the apparently inconsistent results of the literature regarding the farmers' preferred strategies to adapt to climate change. Indeed, while some studies identified that farmers prefer to cope with heat by enlarging their cropping areas but reducing other inputs (Aragón et al., 2021; Chen and Gong, 2021; Amare and Balana, 2023), others found that farmers prefer to cope with heat by doing the opposite (Burke and Emerick, 2016; Cui, 2020; Ji and Cobourn, 2021). Our results show that these opposite patterns are actually consistent with the role of receiving better land property rights, the latter shifting the incentives for farmers to adapt to climate change from extensive to intensive margin strategies.

We finally contribute to the literature on the effects of institutions on economic development (Acemoglu et al., 2019; Adamopoulos et al., 2024), by looking at the particular case of the quality of land property rights (e.g., Libecap and Lueck, 2011). The impacts of property rights on economic development have been the subject of numerous research since Coase (1960), notably regarding its impacts on resources allocation in agriculture (Adamopoulos and Restuccia, 2020; Chari et al., 2021; Chen et al., 2022). We especially illustrate the recent findings by D'Arcy et al. (2024) on the beneficial economic effects of cadasters, showing in particular that the digital Hellenic Cadastre has encouraged Greek farmers to perform defensive land investments in response to greater exposure to heat − which ultimately allowed them to mitigate the heat damage on crop yields.

The paper is organized as follows. Section 2 provides an overview of Greek agriculture and the history on land property rights in Greece. Section 3 presents the data. Section 4 exposes the empirical strategy. Section 5 describes the estimation results. Section 6 discusses and concludes.

2 Background

Our empirical analysis compares Greek farmers' adaptation strategies in response to heat before and after receiving the Hellenic cadastral reform. This section first provides respective overviews on the Greek agriculture and land system (with a focus on the Hellenic Cadastre), before to specify a simple framework explaining how Greek farmers could differently adjust their production decisions to heat exposure depending on the quality of their land property rights.

2.1 Agriculture in Greece

Agriculture serves as the main source of livelihood for most rural communities in Greece (Diao and Song, 2024). Indeed, despite representing only four percent of the Greek GDP in 2010 (the year before our first year of analysis), agriculture still employed about a quarter of the active population of Greece at that time (Eurostat, 2011). These figures largely differ with the remaining of Europe, for which agriculture only represented about two percent of European GDP and employed about four percent of the European workforce at that time (Eurostat, 2011). This means that, contrary to most of the other part of Europe, agriculture in Greece is characterized by a low productivity of labor, which may make it more similar to agriculture in developing countries than in developed countries in many respects. This is particularly evident when looking at the number and size of the farms in the country. With about seven hundred thousands agricultural holdings on its territory in 2010, Greece has indeed for long been among the EU countries with the most farms (Eurostat, 2011) – only Romania (3.8 million farms), Italy (1.6 million), Poland (1.5 million), and Spain (1.0 million) had more in Europe (but are also larger countries in total). Accordingly, Greece present also one of the smallest average farm sizes in the EU, with an average size of about 4.8 ha in 2010 – only Romania (3.4 ha), Cyprus (3.0 ha), and Malta (0.9 ha) reported lower averages. As a result, farming in Greece remains a predominantly family activity, with only ten percent of the agricultural employment relying on off-farm employees (Eurostat, 2011).

With 3.5 million hectares, farmland approximately covered one-fourth of Greece's territory. About half of it is arable land, with wheat, barley and maize constituting about eighty percent of total arable lands in Greece (see Section 3 for further details). A specificity of Greek agriculture is the large proportion of permanent crop plantations, with about a fourth of farmland area dedicated to tree plantations (including olive production) and two percent for vines. The remaining of Greek farmland area is dedicated to other commodities (mostly based on pastures).

2.2 Hellenic cadastral reform in Greece

Greece established its first land system in 1853. Know as the "Υποθηκοφυλάκειο" ("Ipothikofilaki"), this system used paper registries to link legal deeds, easements and disputes to the individuals claiming the plot's ownership. In this "person-based" system, landowners filed their claims at mortgage offices without any standardized land surveys, such that several landowners can claim the ownership of the same property. Additionally, the land records lacked connection to a structured map but are instead described using vague and possibly out-to-date references to remarkable landscape elements (e.g., “between the donkey path and the forest”). This ambiguity in boundaries and the reliance on personal registration led to numerous, overlapping claims and long legal disputes – sometimes lasting up to a decade (Papakostas, 2018). This resulted into potential legal challenges that force purchasers to pay significant transaction fees for legal and mortgage services (Rokos, 2018).

In face of the high transaction costs incurred by the Υποθηκοφυλάκειο land system, Greece launched in 1994 a program to set a “plot-based” cadastre where titles would be directly attached to the land plots via a unique cadastral number. After an initial installation phase where the necessary information technology infrastructure was designed, the proper recording of information began in 2008 in a staggered way across Greek regions. Based on the cadastral diagrams created by the private contractors in charge (created based on orthophoto maps and on-site evidence), landowners from each region had to register their properties and adjust any discrepancies in the boundaries. Such registration of private land was compulsory, with associated fees of 35 euros per plot (reductions were available when registering multiple plots). Once revised, the cadastral database was opened to public review such that landowners could challenge the details of their property records by submitting objections along with supporting evidence and topographic maps. Approximately 10% of properties were contested and reviewed by specialized law committees. Unclaimed properties are ultimately managed and owned by the Greek government (Diao and Song, 2024).

The Hellenic Cadastre was interrupted by the eurozone crisis in 2009 before that any significant progress has been made (Balla et al., 2022; Diao and Song, 2024) – the program covered less than 8% of the Greek territory by that time. The program resumed in 2014 as part of the bailout agreements with the International Monetary Fund, Eurogroup, the European Central Bank and the Greek government. This second round of survey took place in a staggered way, with rapid progress. As a result, Greece succeeded to complete the survey for more than 92% of the country’s area by 2019. Areas for which surveys have been completed during the process have thus switched from the former system based on incomplete land registries to new (complete) land cadastre. A first on-site survey showed that 79% of the landowners believed the land registry would help in resolving land disputes (Tsigarida, 2019). The World Bank (2019) complementary finds that the switch from the old land registries to the new Hellenic Cadastre allows local courts to resolve property disputes more efficiently.

3 Data

This article relies on a set of longitudinal data covering agricultural yields, practices and areas, as well as information on weather and cadastral reform for Greece from 2011 to 2019. We present hereafter our main data sources and variables of interest, before to describe the summary statistics of our sample.

3.1 Data sources and variables

Agricultural variables. The agricultural data comes from the Hellenic Statistical Authority. It provides annual statistics per region for crop yields and areas since 2010, and for machinery since 2013. Agricultural areas can be divided into areas for arable crops, gardens, trees, vineyards, and fallow lands. Following the literature on the impacts of temperature on crop yields (Blanc and Schlenker, 2017), we restrain our analyses on the most common crops, namely (i) wheat, (ii) barley and (iii) maize. These three crops have indeed been the subject of numerous research on the topic (e.g., Lobell et al., 2013; Gammans et al., 2017). They are also the most common arable crops in Greece (and more generally in Europe), occupying together more than 80% of the Greek arable area – the remainder is occupied by arable crops as diverse as rye, oats, rice or sorghum, as well as other even more marginal crops occupying less than 1% of the Greek arable area.

Cadastre program. To exploit the staggered design of the implementation of the Hellenic Cadastre program, we used the information on the year at which the municipalities first received the program, retrieved from the official Hellenic Cadastre website (Diao and Song, 2024). Covering more than 85% of the Greek territory, such a focus on the most recent wave of land registration from 2014 to 2019 has the advantage of being quickly implemented to be a true roll-out reform (Balla et al., 2022). In particular, this second round of survey took an average eleven months per region to complete the cadastral database. To match the nature of the agricultural data provided by the Hellenic Statistical Authority, we aggregated the information on the Cadastre program at the regional unit. This aggregation is complementarilly supported by the fact that the program was really designed at the regional level, such that this administrative division is more relevant than the municipal one to analyze the effect of the Hellenic program.

Ideally, all municipalities within a single region should be uniformly and simultaneously covered by the Cadastre program. However, there were some exceptions given that some municipalities already completed the survey before 2000 during a pilot phase. These pilots were however conducted before the Kallikratis Plan of 2010, which reorganized all of the pre-Kapodistrias administrative structure – that is, municipalities, prefectures, etc. – into 74 regional units. To address the variations in administrative boundaries, we began by recording the year for which each municipality initiated its land registry. As in Diao and Song (2024), we successfully identified 97% of the municipalities from the pre-Kapodistrias period (5,587 out of 5,775). The municipalities that did not match were either lacking clear starting years or could not be precisely located geographically. We then attributed these municipalities within the 74 regional units defined by the current Kallikratis administrative framework.

To define the treatment over these regional units, we applied the following rule: if over 85% of a regional unit had a consistent starting year, we considered that the entire unit was treated by the Cadastre program in that year. Similarly, if more than 85% of a regional unit remained unchanged from 2014 to 2019, we considered that the entire unit was untreated by 2019. Following this criterion, 59 of the 74 regional units were included in our sample. The fifteen remaining ones were regions for which at least 15% of the municipalities were treated over multiple year (even if often consecutive), which we excluded from the sample.

Weather. We access historical weather data from the ERA-5 database, for which daily temperature and precipitation measurements are available over the whole Greece at the 5 arc-minutes resolution – about 5 km × 5 km at the equator – for the whole period of our analysis. Based on minimum and maximum daily temperature data, we recompute the cumulative excess temperature within the growing season – from April 1$^{\text{st}}$ to August 31$^{\text{th}}$ – using the reconstructed temperature distribution *à la* Schlenker and Roberts (2009), where the daily temperature distribution is approximated using a sine interpolation between minimal and maximal temperatures. We then recompute the exposure to temperature usually harmful to crops (known as "killing degree days") as the cumulative time spent above 30°C (expressed in number of days). In addition, we compute the quantity of rainfall accumulated during the growing season to control for the effects of precipitation (expressed in centimeters). To match the nature of our agricultural and cadastral data, we finally attributed these annual data at the regional level using overlapping GIS coordinates, weighting by grid overlapping areas.

3.2 Summary statistics

Our final dataset consists of a balanced panel of 59 regions observed between 2011 and 2019. Table 1 describes the summary statistics in our sample, detailing in one hand the distribution of our outcome of interest (whether on outputs – wheat, barley and maize yields and areas – or inputs), and on the other the distribution of our two treatments (heat and cadastral program) and complementary controls.. It shows that, among the three crop of interest, wheat occupies the largest part of Greek arable land area, but maize presents the highest yields. Together, the three crops occupy on average 81% of the regional arable area. There is a larger heterogeneity of crop areas than crop yields in the sample, with associated coefficient of variation of 2.00, 1.60 and 2.08 for wheat, barley and maize areas respectively, but only 0.31, 0.36 and 0.45 for wheat, barley and maize yields. As commonly identified in the literature (e.g., Blanc and Schlenker, 2017), Table 1 indicates that rainfall is more heterogeneous than temperature (as measured by beneficial degree days), with associated coefficient of variation of 0.68 and 0.05 respectively. Hopefully for our identification strategy, heat is more heterogeneous across our sample, with associated coefficient of variation of 1.06. We couple this source of variation with those associated to the regional access to the new cadastre – which also varies widely in our sample (coefficient of variation of 1.79) – to identify their joint impact on our outcomes of interest.

Table 1: Summary statistics at the regional level (N×T=531).

	Mean	**S.D.**	**Min**	**Median**	**Max**
Wheat yields (tons/ha)	2.49	0.77	0.38	2.59	4.68
Barley yields (tons/ha)	2.23	0.80	0.40	2.30	4.99
Maize yields (tons/ha)	8.95	4.06	0.72	9.82	50.00
Wheat area (ha)	6,314.05	12,626.52	0.00	164.50	64,715.20
Barley area (ha)	1,479.51	2,363.56	0.00	220.50	18,753.90
Maize area (ha)	1,837.91	3,827.09	0.00	60.90	23,862.60
Arable area (ha)	10,839.49	17,515.08	0.00	1,453.50	90,305.10
Tractors (nb./ha)	1.82	12.47	0.00	0.32	220.00
Killing degree days (nb. days)	9.62	10.22	0.00	6.91	48.49
Beneficial degree days (nb. days)	146.52	7.79	112.98	149.22	153
Rainfall (centimeters)	1.90	1.30	0.10	1.74	6.19
Hellenic Cadastre (0/1)	0.24	0.43	0.00	0.00	1.00

Note. The table presents the summary statistics for our sample at the regional level between 2011 and 2019. Our outcome variables are respectively the crop yields and areas, as well as the agricultural inputs. Our two treatment variables are respectively the killing degree days (expressed in numbers of days above 30°C during the growing season – April 1 to August 31) and Hellenic Cadastre (binary variable taking the value one when the region has received the cadastral reform, and zero otherwise). See the text for a full description of the variables and their corresponding sources.

4 Methods

Following the literature on the measurement of weather impacts on agricultural outcomes (Schlenker and Roberts, 2009; Blanc and Schlenker, 2017; Aragón et al., 2021), our preferred specification consists of explaining crop yields in region i in year t as a function of temperature and precipitation during the growing season (defined from April 1st to August 31th for all crops), conditional on region fixed effects. We write this model as:

$$\log(y_{i,t}^k) = \beta_1^k KDD_{i,t}^{30} + \beta_2^k Reform_{i,t} + \beta_3^k KDD_{i,t}^{30} \times Reform_{i,t} + \beta_4^k P_{i,t} + \beta_5^k P_{i,t}^2 + \nu_i^k + \varepsilon_{i,t}^k, \quad (1)$$

where $y_{i,t}^k$ is the yields of crop k ($k \in \{1,2,3\}$ for wheat, barley and maize respectively) in region i and year t (in quantity per area unit), $KDD_{i,t}^{30}$ is the amount of Killing Degree Days during the growing season in t and i (defined as the cumulative time spent above 30°C during the growing season),[1] $P_{i,t}$ is the amount of precipitation that fell during the growing season of t in i (in linear and squared terms), $Reform_{i,t}$ is the dummy variable taking the value one if the cadastral reform has occurred at least two years ago (zero otherwise),[2] ν_i^k is the zip code fixed effect and $\varepsilon_{i,t}^k$ is the remaining error. According to the literature (Hsiang, 2016), the obtained estimates $\hat{\boldsymbol{\beta}}^k$ can be interpreted as causal impacts of contemporaneous weather conditions on yields of crop k. Under some properties of the weather and climate distributions (Mérel and Gammans, 2021), these estimates could even represent the causal impacts of climate change on crop yields.

Following Aragón et al. (2021), we estimate the same types of functions than those in equation (1) but replacing crop yields $y_{i,t}^k$ as dependent variables by crop areas $a_{i,t}^k$ – for $k \in \{1,2,3\}$, in area unit – and total inputs $x_{i,t}^l$ (for $l \in \{1,2,3\}$, standing for quantity of all types tractors, two-wheel and four-wheel tractors per area unit respectively).

5 Results

This section first presents the impacts of the Greek land registry reform in affecting heat damage on crop yields (Section 5.1, before to look at its impacts on farmers' adaptation at the extensive and intensive margins (see Sections 5.2 and 5.3). The section ends by some robustness checks (Section 5.4) and potential mechanism analyses (Section 5.5).

[1] We show in sensitivity analysis that our results are robust to the use of alternative temperature thresholds.

[2] Note that we drop from our sample the fifteen regions – out of the 74 – for which there is no clear start year for the initiation of the land reform – contrary to the other regions, those regions have experienced the reform with mixed starting dates instead. For the 20 regions for which the land registry was already available before 2010, we consider that the treated regions were only those for which more than the half of the agricultural area was registered in the land registry in 2020. This latter case concerns five regions, for which we note $Reform_{i,t} = 1$ for all $t \in [2010:2019]$. For the fifteen remaining regions that received the treatment before 2010 (but for which less than the half of the agricultural area was registered in the land registry in 2020), we note $Reform_{i,t} = 0$ for all $t \in [2010:2019]$.

5.1 Crop yields

Our preferred estimates are presented in Table 2. The different columns correspond to the estimates obtained on our sample for the three considered crops. All of our results suggest that heat decreases crop yields (see first row of Table 2), but that receiving the cadastral reform before the last two years totally offset these detrimental effects (see second row of Table 2). While the former results is fully in line with previous results from the literature (Schlenker and Roberts, 2009; Aragón et al., 2021), the latter ones has not been previously outlined by the literature. These results suggest that better land property rights encourage farmers to better cope with harmful temperatures. Our central estimates indicate that, compared to a situation with the previous (paper, person-based) land registry system, having received the new (digitized, plot-based) land registry has encouraged farmers to offset virtually all of the heat damage on crop yields. Taking into account for the uncertainties around the central estimates suggest that having received the new (digitelized) land registry has led farmers to offset at least twenty-five, twelve and fifty-six percent of the negative effects of abnormal heat exposure on wheat, barley and maize yields respectively (compared to a situation where they have not received the reform).

Table 2: Estimated impacts of heat on crop yields according to the presence of land registry

	Dependent variable: $log(y_{i,t}^k)$		
	Wheat	**Barley**	**Maize**
KDD^{30}	-0.0070 ***	-0.0042 ***	-0.0066 **
	(0.0021)	(0.0019)	(0.0028)
$KDD^{30}\times$ Registry reform	0.0092 ***	0.0075 *	0.0118 ***
	(0.0033)	(0.0043)	(0.0024)
Registry reform	-0.0980	-0.1145 *	-0.1216 ***
	(0.0607)	(0.0581)	(0.0362)
Precipitation controls	Yes	Yes	Yes
Region fixed effects	Yes	Yes	Yes
Adj. R^2	0.7020	0.7701	0.7481
Observations	370	453	383

NOTE. This table presents the estimates of the effects of killing degree days on regional crop yields, depending on whether the region has received the cadastral reform before the last two years. The column headlines refer to crop considered. Killing degree days are measured as the cumulative days spent above 30°C between April 1^{st} to August 31^{th}. Land registry is a binary variable taking the value one if the region has received the cadastral reform at least two years before, and zero otherwise. Standard errors robust to heteroskedasticity and serial correlation at the region level are reported in brackets. *, **, *** indicate p-values lower than 0.1, 0.05 and 0.01.

The results in Table 2 suggest behavioral changes from the farmers having received better land property rights – that ultimately have better offset heat damage on crop yields. In particular, they suggest that these farmers have differently adjust their cropping practices and areas in response to heat exposition after they have received the land registry reform. We examine these switch in adaptation strategies in the two following sections.

5.2 Crop areas

Table 3 report the estimates of the impact of heat on the logarithm of regional area of the three considered crops. In line with Aragón et al. (2021), results in Table 3 suggest that farmers with poor land property rights cope with heat by enlarging crop areas (see first row of Table 3). We extend this result by showing that it only hold in our case when farmers do not access the new land registry. Indeed, Table 3 shows that receiving the cadastral reform before the last two years offset by 50% to 80% the effects of heat on crop areas (see second row of Table 2). Together with results in Table 2, Table 3 suggests that farmers receiving better land property rights move from land-extensification to land-intensification adaptation strategies. That is, farmers with better land property rights are encouraged to adapt at the intensive margin – i.e. saving crop yields – rather than at the extensive margin (i.e. expanding crop areas). These results suggest that farmers with better land property rights are better able to secure their land investments, ultimately ensuring them with higher crop yields.

Table 3: Estimated impacts of heat on crop areas according to the presence of land registry

	Dependent variable: $log(1 + a^k_{i,t})$		
	Wheat	**Barley**	**Maize**
KDD^{30}	0.0066	0.0215 ***	0.0215 ***
	(0.0118)	(0.0054)	(0.0057)
$KDD^{30} \times$ Registry reform	-0.0128 *	-0.0149 **	-0.0201 **
	(0.0066)	(0.0067)	(0.0081)
Registry reform	-0.0782	0.2535 *	-0.1776
	(0.1123)	(0.1272)	(0.1922)
Precipitation controls	Yes	Yes	Yes
Region fixed effects	Yes	Yes	Yes
Adj. R^2	0.9139	0.8928	0.9531
Observations	531	531	531

Note. This table presents the estimates of the effects of killing degree days on regional crop areas, depending on whether the region has received the cadastral reform before the last two years. The column headlines refer to crop considered. Killing degree days are measured as the cumulative days spent above 30°C between April 1^{st} to August 31^{th}. Land registry is a binary variable taking the value one if the region has received the cadastral reform at least two years before, and zero otherwise. Standard errors robust to heteroskedasticity and serial correlation at the region level are reported in brackets. *, **, *** indicate p-values lower than 0.1, 0.05 and 0.01.

5.3 Agricultural inputs

Table 4 report the estimates of the impact of heat on the logarithm of agricultural inputs, expressed in quantity per area unit (including all of the agricultural area). In line with our previous interpretation, results in Table 4 suggest that farmers receiving better land property rights move from land-extensification to land-intensification adaptation strategies. Formally, Table 4 shows that farmers with better land property rights are encouraged to adapt at the intensive margin when facing greater harmful temperature. Together with results in Tables 2 and 3, these results suggest that farmers are better able to secure their land investments when receiving better land property rights, ultimately ensuring them with higher crop yields.

Table 4: Estimated impacts of heat on inputs according to the presence of land registry

	Dependent variable: $log(1 + x_{i,t}^k)$		
	All tractors	**Two-wheel tractors**	**Four-wheel tractors**
KDD^{30}	-0.0099 ***	-0.0138 ***	-0.0071 *
	(0.0029)	(0.0042)	(0.0036)
$KDD^{30}\times$ Registry reform	0.0106 **	0.0265 *	0.0065
	(0.0043)	(0.0151)	(0.0046)
Registry reform	-0.1655 *	-0.1335	-0.1502
	(0.0858)	(0.217)	(0.0964)
Precipitation controls	Yes	Yes	Yes
Region fixed effects	Yes	Yes	Yes
R^2	0.8495	0.9043	0.7849
Observations	493	493	494

NOTE. This table presents the estimates of the effects of killing degree days on the regional use of agricultural inputs (expressed in quantity per area unit), depending on whether the region has received the cadastral reform before the last two years. The column headlines refer to crop considered. Killing degree days are measured as the cumulative days spent above 30°C between April 1^{st} to August 31^{th}. Land registry is a binary variable taking the value one if the region has received the cadastral reform at least two years before, and zero otherwise. Standard errors robust to heteroskedasticity and serial correlation at the region level are reported in brackets. *, **, *** indicate p-values lower than 0.1, 0.05 and 0.01.

5.4 Sensitivity analyses

Results in Appendix A1 show that our results hold to the change in the heat definition. Accounting for the growing-season temperature above 32°C instead of 30°C has minor effects on our results regarding the impacts of the Greek land registry reform in affecting heat damage on crop yields or farmers' adaptation (whether at the extensive and intensive margins.

5.5 Alternative potential mechanisms

Our empirical results consistently indicate that farmers receiving better land property rights switch from land-extensification (i.e., adjustment of farmland area) to land-intensification strategies (i.e., adjustment of other inputs), which ultimately reduce heat damage on crop yields. Yet, this interpretation may be challenged by alternative mechanisms. This section investigate this issue, looking at the particular case of fallow lands.

Table 5 display the results of heat impacts on fallows in function of the land registry reform. They suggest that fallowing lands is not an adaptation margin to greater heat exposure, but that receiving better land property rights significantly increase the area devoted to fallows. This latter result is a standard results in the literature on land property rights (e.g., Le Rossignol et al., 2024), as more secure land property rights encourage farmers to implement such cropping practives improving land productivity in the long term (Besley, 1995).

Table 5: Estimated impacts of heat on fallow areas according to the presence of land registry

	Dependent variable: $log(1 + a_{i,t}^{fallow})$
KDD^{30}	0.0024
	(0.0025)
KDD^{30} × Registry reform	-0.0034
	(0.0026)
Registry reform	0.4969 ***
	(0.1242)
Precipitation controls	Yes
Region fixed effects	Yes
Adj. R^2	0.7691
Observations	501

NOTE. This table presents the estimates of the effects of killing degree days on regional fallow areas, depending on whether the region has received the cadastral reform before the last two years. Killing degree days are measured as the cumulative days spent above 30°C between April 1st to August 31th. Land registry is a binary variable taking the value one if the region has received the cadastral reform at least two years before, and zero otherwise. Standard errors robust to heteroskedasticity and serial correlation at the region level are reported in brackets. *, **, *** indicate p-values lower than 0.1, 0.05 and 0.01.

6 Conclusion

This paper demonstrates the critical role of land property rights in shaping farmers' adaptation strategies to climate-induced heat stress. Using the natural experiment of the Hellenic Cadastre reform in Greece, we show that improved land tenure systems significantly mitigate the negative impacts of abnormal heat exposure on crop yields. Farmers with more secure property rights are less likely to expand cropland areas and instead intensify input use, such as machinery, to adapt to increasing heat exposure. These findings resolve inconsistencies in prior research on adaptation behaviors, illustrating that institutional quality drives farmers toward intensive rather than extensive margin strategies. Whereas other analyses remain to be done in the context of this paper, our first results underscore the importance of strengthening land institutions as a means of fostering resilience to climate change in agriculture, contributing to broader discussions on the intersection of property rights and economic development.

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7 Appendices

A1 Sensitivity analysis: alternative KDD measurements

Tables A1, A2 and A3 respectively display the estimates of the impacts of heat on crop yields, crop areas and agricultural inputs according to the presence of land registry, with KDD measured as cumulative temperature over 32°C (instead of 30°C in the preferred analysis). These results show that farmers receiving better land property rights move from land-extensification to land-intensification adaptation strategies, ultimately ensuring them with higher crop yields.

Table A1: Estimated impacts of heat on crop yields according to the presence of land registry, with KDD measured as cumulative temperature over 32°C

	Dependent variable: $log(y^k_{i,t})$		
	Wheat	**Barley**	**Maize**
KDD^{30}	-0.0109 ***	-0.0061 **	-0.0095 ***
	(0.0032)	(0.0029)	(0.0033)
$KDD^{30}\times$ Registry reform	0.0151 ***	0.0096	0.017 ***
	(0.0047)	(0.0067)	(0.0038)
Registry reform	-0.0653	-0.0694	-0.0628 *
	(0.046)	(0.052)	(0.0324)
Precipitation controls	Yes	Yes	Yes
Region fixed effects	Yes	Yes	Yes
R^2	0.7019	0.7698	0.7477
Observations	370	453	383

NOTE. This table presents the estimates of the effects of killing degree days on regional crop yields, depending on whether the region has received the cadastral reform before the last two years. The column headlines refer to crop considered. Killing degree days are measured as the cumulative days spent above 32°C between April 1st to August 31th. Land registry is a binary variable taking the value one if the region has received the cadastral reform at least two years before, and zero otherwise. Standard errors robust to heteroskedasticity and serial correlation at the region level are reported in brackets. *, **, *** indicate p-values lower than 0.1, 0.05 and 0.01.

Table A2: Estimated impacts of heat on crop areas according to the presence of land registry, with KDD measured as cumulative temperature over 32°C

	Dependent variable: $log(a_{i,t}^k)$		
	Wheat	**Barley**	**Maize**
KDD^{30}	0.0319 ***	0.0326 ***	0.042 ***
	(0.0074)	(0.0095)	(0.008)
$KDD^{30}\times$ Registry reform	-0.0255 ***	-0.0203 *	-0.0317 *
	(0.0075)	(0.0121)	(0.0177)
Registry reform	-0.1146	0.1707	-0.2634
	(0.0728)	(0.1362)	(0.1956)
Precipitation controls	Yes	Yes	Yes
Region fixed effects	Yes	Yes	Yes
R^2	0.9711	0.9105	0.9387
Observations	370	453	383

NOTE. This table presents the estimates of the effects of killing degree days on regional crop areas, depending on whether the region has received the cadastral reform before the last two years. The column headlines refer to crop considered. Killing degree days are measured as the cumulative days spent above 32°C between April 1st to August 31th. Land registry is a binary variable taking the value one if the region has received the cadastral reform at least two years before, and zero otherwise. Standard errors robust to heteroskedasticity and serial correlation at the region level are reported in brackets. *, **, *** indicate p-values lower than 0.1, 0.05 and 0.01.

Table A3: Estimated impacts of heat on inputs according to the presence of land registry, with KDD measured as cumulative temperature over 32°C

	Dependent variable: $log(x_{i,t}^k)$		
	All tractors	**Two-wheel tractors**	**Four-wheel tractors**
KDD^{30}	-0.0137 ***	-0.0191 ***	-0.0097 *
	(0.004)	(0.0056)	(0.0052)
$KDD^{30}\times$ Registry reform	0.0195 ***	0.0419 *	0.0136 **
	(0.0061)	(0.0215)	(0.0067)
Registry reform	-0.1426 **	-0.0267	-0.1476 **
	(0.0632)	(0.1648)	(0.0733)
Precipitation controls	Yes	Yes	Yes
Region fixed effects	Yes	Yes	Yes
R^2	0.8494	0.9042	0.7849
Observations	493	493	494

NOTE. This table presents the estimates of the effects of killing degree days on the regional use of agricultural inputs (expressed in quantity per area unit), depending on whether the region has received the cadastral reform before the last two years. The column headlines refer to crop considered. Killing degree days are measured as the cumulative days spent above 30°C between April 1st to August 31th. Land registry is a binary variable taking the value one if the region has received the cadastral reform at least two years before, and zero otherwise. Standard errors robust to heteroskedasticity and serial correlation at the region level are reported in brackets. *, **, *** indicate p-values lower than 0.1, 0.05 and 0.01.