Adapting to climate change with (in)complete land property rights: Evidence from the Greece land registry reform

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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 offset most (if not all) of the crop losses induced by higher heat exposure. This pattern is consistent with our theory indicating that farmers receiving better land property rights should 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, indeed, farmers without the reform respond to an additional degree day above 28°C by enlarging crop area from 0.2 to 0.4 percent, while farmers having received better land property rights do not adjust along this margin. Conversely, farmers having received the reform increase their use of labor and irrigation by 0.4 and 0.2 percent respectively for an additional degree day, while those without do not adjust these inputs. Finally, farmers having received the reform rely more on machinery by 0.1 percent for an additional degree day, while they reduce it by 0.2 without the reform. These results underline the crucial role of institutions in encouraging our societies to adapt to climate change.

Keywords: adaptation incentives, adaptation to climate change, institutional quality, land tenure, land regulation, weather shocks.

JEL Codes: P14, Q15, Q54

1 Introduction

Hundreds of studies have documented the detrimental effects of heat on crop yields worldwide (Schlenker and Roberts, 2009; Lobell et al., 2011, 2013; Burke and Emerick, 2016; Wing et al., 2021). While early studies focused on quantifying yield reductions (see Blanc and Schlenker, 2017, for a review), recent research has shifted to analyzing proper adaptation strategies (Aragón et al., 2021; Jagnani et al., 2021; Bareille and Chakir, 2024). These analyses consistently show that heat exposure reduces crop yields (once temperature exceeds 28°C or so), and encourages farmers to adjust their cropping practices and areas (referred to as "*adaptation at the intensive margin*" and "*adaptation at the extensive margin*" hereinafter). However, the direction and magnitude of these behaviors remain debated. For example, Cui (2020) and Ji and Cobourn (2021) found that US farmers reduce croplands in response to greater heat exposure, while Aragón et al. (2021), He and Chen (2022) and Amare and Balana (2023) respectively showed that Peruvian, Ethiopian 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 to greater heat exposure, while Chen and Gong (2021), Jagnani et al. (2021) and Amare and Balana (2023) respectively showed that Chinese, Kenyan and Nigerian farmers instead reduce theirs. We argue below that these apparently contrasting results are likely shaped by the – so-far ignored – varying quality of land property rights in aforementioned countries.

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 first develop a theoretical model where household farmers' adaptation efforts at the intensive margin increasingly reduce the heat damage on crop yields, but where the extent of the returns are determined by the quality of land property rights. Compared to a situation with clearly-defined land property rights, households with incomplete property rights under-invest in adaptation strategies at the intensive margin because they cannot secure their land returns (which can be partly grabbed by others), ultimately translating into smaller crop yields. Conversely, households with incomplete land property rights are encouraged to adapt at the extensive margin by enlarging their croplands to mitigate the negative impacts of heat on their revenues.

To test the model implications, we leverage the recent land reform in Greece, known as Hellenic Cadastre. This land reform has set up a new land tenure system with mandatory land registry of all private land parcels and digitally delimited boundaries on cadastral maps. The reform was rolled out in a staggered way, covering most Greek regions between 2014 and 2019.[1] We combine the timing of this reform with annual weather and agricultural statistics to create a balanced panel of 57 regions between 2011 and 2019.[2] Measuring heat exposure as days above 28°C during the growing season, we assess how stronger land rights following the reform modified the impacts of heat on the yields of Greece's three main crops (wheat, barley, and maize, accounting for 80% of arable land) and farmers' adaptation strategies, including changes in crop areas (extensive margin adaptation) and agricultural inputs per hectare (intensive margin adaptation; i.e., machinery, labor, and irrigation specifically).

Our identification strategy exploits within-sample variations in our two treatments – heat exposure and cadastral reform timing – to compare (i) the effects of region-specific abnormal annual heat deviations on crop yields, areas, and input use between (ii) regions that have received the reform and (iii) those who have not (or not yet). Our preferred specification explicitly links our outcomes of interest and our two treatment variables *independently* and *in interaction*, conditionally on various controls and region fixed effects. We specifically focus on the amplitude and sign of the estimated interaction term to assess how land property rights shape heat impacts on yields and adaptation strategies.

All of our empirical results support our theoretical propositions. Formally, our results indicate that farmers having received the cadastral reform respectively offset at least 30, 10 and 63 percents of the negative effects of abnormal heat exposure on wheat, barley and maize yields (compared to a situation where they would have not received the reform). While an additional degree day above 28°C reduces the yields of the three crop by about 0.1 percent without the reform, our preferred estimates even indicate that farmers having received the reform can virtually offset all of the detrimental effects of abnormal heat exposure on crop yields. These results are robust to numerous robustness checks, such as the use of alternative heat or land registry measurements, the correction for spatial correlation or the inclusion of additional controls (e.g., international crop prices, quadratic time trends or year fixed effects), providing insurance on the reliability of our estimates.

This reduction in heat damage to crop yields aligns with evidence that farmers receiving the reform shift from land-extensification (adjusting farmland areas) to land-intensification strategies (adjusting other inputs). Specifically, our preferred estimates show that farmers without the reform

[1] Early pilot programs have started in 1998 and paused by the Euro crisis in 2008. We focus on the most recent wave of land registration from 2014 to 2019, because it covered 85% of the country, allowing clear identification of its impact.

[2] The panel data begins in 2011, as it is the first year in which the data is aggregated under the current Kallistratis administrative division boundaries.

respond to an additional degree day by enlarging crop area from 0.2 to 0.4 percent, while those with the reform do not adjust along this margin, or, if so, in a very limited extent – i.e., farmers with the reform limit cropland expansion by 70 to 95 percents compared to those without. The reduced responses at the extensive margin are replaced by intensive margin adjustments: while farmers without the reform do not adjust labor or irrigation to additional heat, they intensify their respective utilization by 0.4% and 0.2% per additional degree day. Farmers with the reform also increase machinery use by 0.1%, whereas those without reduce it by 0.2%. Robust to numerous changes in our empirical setting, these results strongly support the idea that farmers receiving better land rights reduce heat damage on crop yields by switching from land-extensification to land-intensification adaptation strategies. As no significant interaction is observed for other outcomes (e.g., other farmland areas, fire occurrence, livestock density), we rule out that reduced heat damage on crop yields can stem from anything else than the effects of land property rights in shifting the way farmers adapt to heat exposure.

Our work contributes to three bodies of literature. First, we add to the extensive literature measuring the detrimental effects of heat on crop yields (Auffhammer et al., 2013; Blanc and Schlenker, 2017; Carter et al., 2018), by showing that the extent of heat damage on agriculture depends on the quality of farmers' land property rights. While our results indicate that heat unambiguously reduces crop yields when Greek farmers have incomplete rights (by the same extent than most current estimates; see, e.g., Wing et al., 2021, for a global assessment), they show that farmers who have received the cadastral reform can offset most of these detrimental effects. These results indicate a clear role for institutions in encouraging our societies to adapt to climate change.[3] 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 (Jagnani et al., 2021; Cui and Xie, 2022; He and Chen, 2022). We particularly shed new lights on the apparently inconsistent results previously highlighted in this literature – some studies identifying that farmers prefer to cope with heat by enlarging their croplands but reducing other inputs (Aragón et al., 2021; Chen and Gong, 2021; He and Chen, 2022; Amare and Balana, 2023), while others finding the opposite (Cui, 2020; Ji and Cobourn, 2021; Bareille and Chakir, 2024). Our results reconcile these opposite patterns by highlighting the role of complete

[3] See Bezabih et al. (2021), Henry (2022) and Murken et al. (2024) for related research with alternative methods in the context of agriculture.

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, before to present the analytic framework. Section 4 presents the data. Section 5 exposes the empirical strategy. Section 6 describes the estimation results. Section 7 discusses and concludes.

2 Background

Our empirical analysis examines Greek farmers' adaptation strategies to heat exposure before and after the implementation of the Hellenic Cadastre reform. This section provides an overview of Greek agriculture and land tenure system, with a particular emphasis on the Hellenic Cadastre program.

2.1 Agriculture in Greece

Agriculture remains a primary source of livelihood for the majority of rural communities in Greece. Despite accounting for only four percents of Greek GDP in 2010—the year preceding the start of our analysis—agriculture employed approximately one-quarter of the active population (Eurostat, 2011). These figures contrast sharply with the rest of Europe, where agriculture constituted just two percents of GDP and engaged only about 4% of the workforce during the same period (Eurostat, 2011). This disparity highlights the relatively low labor productivity of Greek agriculture, aligning it more closely with agricultural systems in developing countries rather than those in developed economies.

Greece had approximately 700,000 agricultural holdings in 2010, making it one of the EU countries with the highest number of farms, following Romania, Italy, Poland, and Spain (Eurostat, 2011). However, it also has one of the smallest average farm sizes in the EU at 4.8 hectares—larger only than Romania, Cyprus, and Malta. Farming remains predominantly a family activity, with just ten percents of agricultural employment relying on off-farm labor (Eurostat, 2011).

This fragmented farming landscape is mirrored in the use of agricultural land. Farmland covers about one-fourth of Greece's territory, totaling 3.5 million hectares. Half of this area is arable land, predominantly used for wheat, barley, and maize, which account for eighty percents of the arable area. Permanent crops like olive trees occupy a quarter of the farmland, while vines make up two percents. The remaining farmland is primarily used for fallows and pastures.

The Greek agricultural sector faces significant challenges from climate change, with rising temperatures, prolonged droughts, and increased frequency of extreme weather events posing serious threats to productivity. Greece's three main crops grown (wheat, barley and maize) are among the most significantly damaged by the rise in temperature (IPCC, 2022). Direct economic losses to Greek agriculture from climate impacts are estimated to range between €437 million and €1 billion annually by mid-century, with indirect effects on related sectors, such as food processing and tourism, doubling these losses (Georgopoulou et al., 2024). Regions such as Thessaly and Central Macedonia, where agricultural activity is concentrated, are expected to bear the brunt of these changes (Founda et al., 2022), further exacerbating socio-economic vulnerabilities in rural areas.

The combination of small-scale, family-run farms and the reliance on vulnerable crops such as wheat, barley and maize magnifies the potential impacts of climate shocks. Studying Greece offers a unique opportunity to analyze how climate change, coupled with incomplete property rights, affect farmers' adaptation strategies. Insights gained from this study not only address pressing local challenges but also contribute to broader discussions on climate resilience in regions with fragmented agricultural systems and similar climatic vulnerabilities.

2.2 Hellenic cadastral reform in Greece

Greece has long struggled with widespread land disputes driven by unclear property boundaries and overlapping claims. The roots of these challenges can be traced back to the country's first land registration system, established in 1853, which was deeply flawed from the outset.

This initial system relied on personal registration rather than comprehensive land surveys or systematic maps, which became the root of Greece's ongoing land registry issues. Landowners registered their claims at mortgage offices, where land titles, contracts, and mortgages were kept in paper form and sorted alphabetically by surname. The land records were not linked to a structured survey map but instead relied on imprecise and potentially outdated descriptions referencing notable landscape features, such as “between the donkey path and the forest.” The absence of systematic land surveys further contributed to inconsistent property boundaries, leading to land disputes that could take years – sometimes even a decade – to resolve (Papakostas, 2018). These prolonged legal challenges often force purchasers to incur significant transaction costs for legal and mortgage services (Rokos, 2018).

In response to the high transaction costs associated with the initial land administration system, Greece initiated a cadastral reform in 1994, introducing a “plot-based” cadastre. This system sought to attach property titles directly to individual land plots using unique cadastral identification numbers, thereby enhancing the clarity and security of property rights. Following an initial phase dedicated to the design and implementation of the requisite information technology infrastructure, systematic recording of land-related data began in 2008. This process was implemented progressively across the country’s regions, reflecting the staggered nature of the reform’s deployment. Using cadastral diagrams prepared by private contractors—developed based on orthophoto maps and on-site evidence—landowners in each region were required to register their properties and reconcile any discrepancies in boundaries. Registration of private land was mandatory, accompanied by a fee of 35 euros per plot, with discounts available for the registration of multiple plots. After revisions, the cadastral database was made publicly accessible, allowing landowners to challenge the recorded details of their properties by submitting formal objections supported by evidence and topographic maps. Approximately 10% of properties were contested and reviewed by specialized legal committees. Properties that remain unclaimed are eventually managed and owned by the Greek government.

The progress of the Hellenic Cadastre was significantly disrupted by the eurozone crisis in 2009, at which point less than 8% of the Greek territory had been covered (Balla et al., 2022). The program resumed in 2014 as part of the bailout agreements involving the International Monetary Fund, the Eurogroup, the European Central Bank, and the Greek government. The subsequent phase of the survey was implemented in a staggered manner, with rapid advancements. By 2019, Greece had successfully completed cadastral surveys for more than 92% of the country’s area (and about 85% between 2014 and 2019). Regions where surveys were completed transitioned from the previous system of incomplete land registries to a comprehensive cadastral system. An initial on-site survey indicated that 79% of landowners believed the new cadastre would contribute to resolving land disputes (Tsigarida, 2019). Supporting this, World Bank (2019) found that the shift from the old land registries to the Hellenic Cadastre has enabled local courts to resolve property disputes more efficiently.

We exploit this reform to compare the agricultural impacts of heat exposure with initial and new land property rights. Next section provides a rationale explaining the expect effects of better land quality rights in face of higher heat exposure.

3 Analytical framework: towards a theory linking land tenure, farmers' adaptation and crop production

We develop below a simple framework to examine production decisions in response to higher heat exposure under varying levels of land security. Without loss of generality, assume that a farmer is initially endowed with one unit of uncultivated land. A fraction $0 \leq \alpha \leq 1$ of this land is of low quality and the rest $(1 - \alpha)$ is of high quality, both known from the farmer. Without loss of generality, we assume that $\alpha = 0$ reflect the initial situation without climate change. Conversely, we assume that α increases when heat exposure increases, with α tending towards one when heat exceeds a threshold. In other words, $\alpha > 0$ reflects the direct impacts of climate change on land quality, which then translates into agricultural productivity (see below).

In response to higher heat exposure, the farmer first decides the area to be cultivated, on both the high quality lands $0 \leq L_h \leq 1 - \alpha$ and the low quality lands $0 \leq L_l \leq \alpha$, with the total cultivated land being $L = L_h + L_l$. Once cultivated, the crop output on the high and low quality land worth P_h and P_l correspondingly (in value per area unit), with $P_h > P_l$.[4]

The farmer can additionally decide to further respond to higher heat exposure by improving part of low quality lands K with suitable practices (e.g., via investing into new machinery or irrigation systems) to turn it into high quality lands, with $0 \leq K \leq \alpha L$.[5] The cost of cultivating and improving land is r and c respectively, measured in crop output for simplicity. We focus on the non-trivial cases where it is profitable to cultivate low quality land ($P_h > r + c$) and to make land improvement ($P_h - P_l > r$).

Following the literature on incomplete property rights (Allen, 2002), we assume a farmer faces a land disputes constraint T under insecure tenure. If the total crop output exceeds T, the neighboring

[4] One can think that these latter values reflect the differences in crop yields between high and low quality lands. Under these latter conditions, higher α induced by higher heat exposure would typically reduced crop yields, as standardly found in the literature (e.g., Schlenker and Roberts, 2009; Aragón et al., 2021; Bareille and Chakir, 2024).

[5] For simplicity, we assume it is not worthwhile to improve the high quality land. Relaxing this assumption would not change the results, so long as less input is required to improve high compared to low quality lands. Note that farmers implementing higher K in response to higher heat exposure (and thus higher α) typically reflect farmers' adaptation at the intensive margin. The choice regarding L reflects the adaptation at the extensive margin.

landowner would find it profitable to initiate a land dispute and take over the contested land. The farmer's maximization problem is then formulated as:

$$
\begin{aligned}
&\max_{L,K} \quad \pi = P_h(L_h + K) + P_l(L_l - K) - cL - rK, \\
&\text{s.t.} \quad 0 \leq L_l \leq \alpha, \quad 0 \leq L_h \leq 1-\alpha, \quad 0 \leq K \leq L_l, \quad P_h(L_h + K) + P_l(L_l - K) \leq \overline{T}.
\end{aligned} \tag{1}
$$

In the trivial case where cultivating low quality land is less profitable than improving it (i.e., $P_l - c < P_h - P_l - r$), the optimal solution is to first cultivate the high quality land and then cultivate and improve the low quality land until the total crop output reaches T: $L^* = \frac{T}{P_h}$ $K^* = max\{\frac{T}{P_h} - 1 + \alpha, 0\}$. Yet, given that most land is not improved (e.g., only 15% of Greek arable lands were irrigated in 2011, i.e., at the beginning of our panel; see Section 4), it is more reasonable to assume that cultivating low quality land is more profitable than improving it: $P_l - c > P_h - P_l - r$. The optimal solution is divided into three cases depending on the level of tenure security T, summarized into Figure 1.

Case 1: insecure tenure. When $T \leq (1-\alpha)P_h + \alpha P_l$, the farmer sequentially cultivates the high quality land and the low quality land until the total crop output reaches T. No land is improved due to the insecure property rights. As illustrated in Figure 1 (1a-b), higher heat exposure lowers the crop output, allowing the farmer to increase the cultivated area until all land has been cultivated. The solution is:

$$
\begin{aligned}
K^* = 0 \ , \ L^* = max\left\{\frac{T}{P_h}, \frac{T - (1-\alpha)P_h}{P_l} + 1 - \alpha\right\}, \\
L_h^* = min\left\{\frac{T}{P_h}, 1-\alpha\right\} \ , \ L_l^* = max\left\{0, \frac{T - (1-\alpha)P_h}{P_l}\right\}.
\end{aligned} \tag{2}
$$

Case 2: intermediate tenure. When $(1-\alpha)P_h + \alpha P_l < T < P_h$, all lands can be cultivated without inviting land disputes ($L^* = 1$). Yet, not all land improvements can be made. The farmer typically improves land until the total crop output reaches T. As illustrated in Figure 1 (2a-c), when higher heat exposure decreases the crop output to below the land dispute constraint T, the farmer starts to improve the land (K^* turns from null to positive). The solution becomes:

$$
K^* = min\left\{0, \frac{T - (1-\alpha)P_h - \alpha P_l}{P_h - P_l}\right\} \ , \ L^* = 1 \ , \ L_h^* = 1 - \alpha \ , \ L_l^* = \alpha. \tag{3}
$$

Case 3: complete tenure. When $T > P_h$, the land disputes are no longer a constraint, and the land is fully cultivated and improved ($K^* = \alpha$ and $L^* = 1$). As illustrated in Figure 1 (3a-b), the

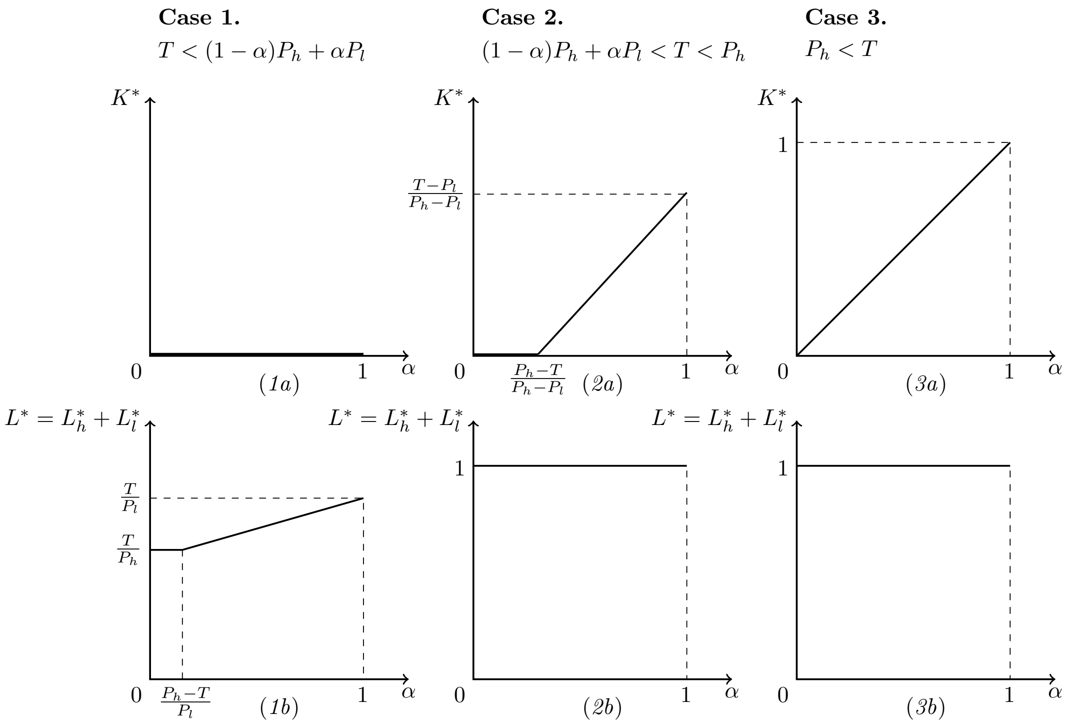


Figure 1: Farmer' adaptation strategies depending on land property rights

NOTE. The figure displays the farmer's optimal responses to higher heat exposure depending on the extent of land property rights. The figure is divided into three columns, (i) the leftest-hand column reflecting the "insecure tenure" case, (ii) the rightest-hand column reflecting the "secure tenure" case and (iii) those in the middle reflecting an intermediate case. The farmer's adaptation responses are divided into those at the intensive margin (first line, reflecting the investment in capital to improve land quality) and those at the extensive margin (second line, reflecting the proportion of the farm cropped). Those latter line is split into land of low and high quality in Figure A1 of the Supplementary Materials, reflecting the proportions of cropped lands with respectively low and high quality. Determined analytically within Section 3, the relations depicted into each sub-figure can be compared one to another.

damage induced by higher heat exposure only encourages the farmer to improve more land. The solution becomes:

$$K^* = \alpha \ , \ L^* = 1 \ , \ L_h^* = 1 - \alpha \ , \ L_l^* = \alpha. \tag{4}$$

Note that, in this latter case, the value of the crop output is P_h for the whole land. That is, the farmer's adaptation at the intensive margin virtually allows offsetting all of the detrimental effects of heat on crop yields.

The above analyses shows that the farmer's response to higher heat exposure at both margins hinges on the level of tenure security T. When T is small, the farmer responds to higher heat exposure (i.e., to larger values of α) by enlarging cultivated area without changing other agricultural inputs. When T is large, the farmer responds to higher heat exposure by increasing other inputs without enlarging cultivated area. Moreover, given farmers use more inputs in the latter than in their former case, the crop outputs on the cultivated lands – i.e., the crop yields – are higher when T is large. We thus derive the following implications:

Implication 1. *Under insecure tenure, cultivated area increases and irrigated area stays the same when heat exposure increases.*

Implication 2. *Under secure tenure, cultivated area stays the same and irrigated area increases when heat exposure increases.*

Implication 3. *For the same heat exposure, the crop yields of the cultivated lands are higher under securer tenure.*

4 Data

To test our theoretical implications, we compiled a panel dataset covering agricultural yields, areas and inputs, as well as data on weather and cadastral reform for Greece from 2011 to 2019. The panel begins in 2011, marking the first year of the current Kallikratis administrative division, which replaced the former Kapodistrias Plan.

4.1 Data sources and variables

Hellenic Cadastre program. To exploit the staggered implementation of the Hellenic Cadastre program, we used information on the year each municipality first received the program, retrieved from the official Hellenic Cadastre website. Covering more than 85% of Greek territory, the most recent wave of land registration (2014–2019) was rapidly implemented as 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 agricultural data provided by the Hellenic Statistical Authority, we aggregated the information on the Cadastre program at the regional unit. This aggregation is furthur justified the program's design, which was structured at the regional level, making the administrative division more relevant than the municipal level for analyzing the program's effects.

Ideally, all municipalities within a single region should have been uniformly and simultaneously covered by the Cadastre program. However, some municipalities had already completed the survey before 2000 as part of a pilot phase. These pilots were conducted prior to the 2010 Kallikratis Plan, which reorganized the pre-Kapodistrias administrative structure—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 illustrated in Figure A2 of the Supplementary Materials. 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 Kalliskratis 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, 57 of the 74 regional units were included in our sample, as illustrated in Figure 2. The 17 remaining ones were regions for which at least 15% of the municipalities were treated over multiple years (even if often consecutive), which we excluded from the sample. Two of them are additionally excluded because not cultivating wheat, barley or maize during our period of analysis.

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 $\times$ 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 – defined from April 1st to August 31th for all crops – 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 28°C (expressed in number of degree days).[6] In addition, we compute the amount of rainfall accumulated during the growing season to control for the effects of precipitation (measured in centimeters). We aggregate these annual data at the regional level using overlapping geocoded layers.

Figure A3 in Supplementary Materials illustrates the average number of killing degree days between 2011 and 2019 across Greece. It is not surprising that heat exposure is spatially correlated across Greek regions, with higher killing degree days in southern and XXXX Greece.

[6] We show in Section 6.4 that our results are robust to alternative measurements of heat exposure, notably with higher thresholds (30°C, 32°C or 34°C). They are also robust to the use of heat over the whole year (instead of the growing season only).

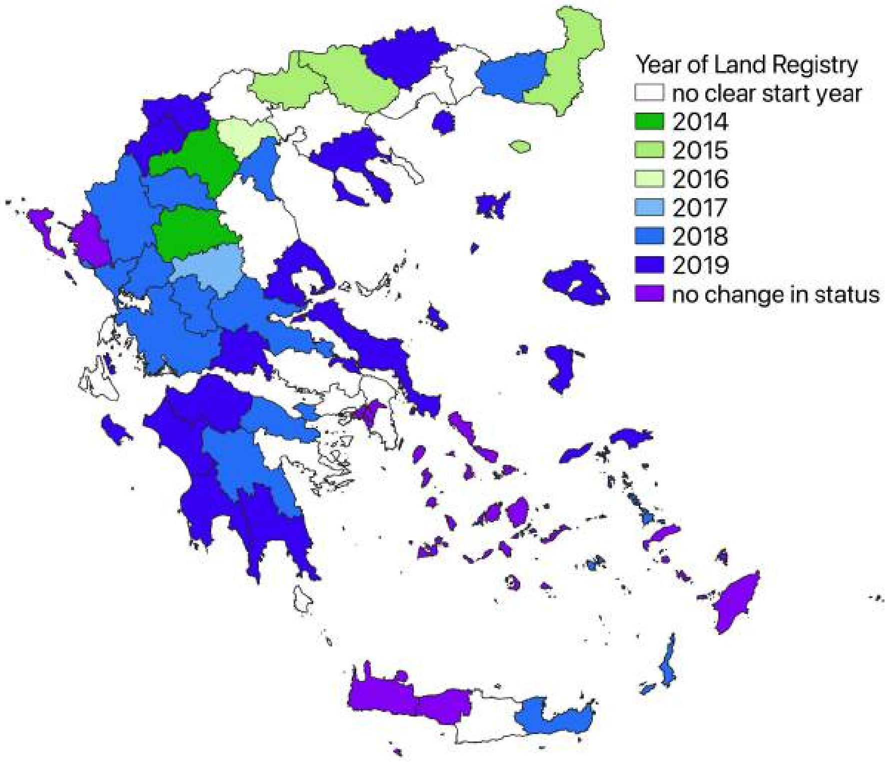


Figure 2: Year of Land Registry at the Regional Unit Level

NOTE. This figure illustrates the year in which each of the regional units in our sample began implementing the Hellenic Cadastre program. Regions are colored based on their first year of program initiation, as determined by the aggregation of municipal-level starting years in Figure A2 of the Supplementary Materials and if over 85% of the region had a consistent starting year. Regions excluded from the analysis fall into one of three categories: (i) regions where more than 15% of municipalities initiated the program in multiple, non-consecutive years (colored in white), (ii) regions without sufficient agricultural activity for wheat, barley, or maize, or (iii) regions not covered by the program between 2014 and 2019 (colored in violet).

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 variable inputs and machinery since 2013. Agricultural areas can be divided into areas for arable crops, permanent crops (orchards and vineyards), gardens 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. Unlike climate change, average crop yields and crop areas (see Figure A9 in Supplementary Materials) over the period are less spatially correlated.

Regarding the information on agricultural inputs, the Hellenic Statistical Authority provide tables on more than thirty different types of agricultural machinery (e.g., irrigation systems or tractors). Data on labor comes from.....

4.2 Summary statistics

Our final dataset consists of a balanced panel of 57 regions observed between 2011 and 2019. Table 1 describes the summary statistics in our sample, detailing in one hand the distribution of our outcomes of interest (whether on outputs – wheat, barley and maize yields and areas – or inputs – i.e., machinery, labor and irrigation), and on the other the distribution of our two treatments (heat and cadastral program) and complementary controls.. It shows that, among the three crops of interest, wheat occupies the largest part of Greek arable land area, but maize presents the highest yields. 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. Heat is notably more heterogeneous across our sample with a coefficient of variation of 1.06, making it well-suited for our identification strategy. 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.

5 Methods

This section explains the empirical strategy of the paper. Section 5 details our econometric modeling, while Section 5.2 discusses our identification strategy.

5.1 Econometric modeling

Following the literature on the measurement of weather impacts on agricultural outcomes (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, conditional on region fixed effects. We write this model as:

$$\log(y_{i,t}^k) = \beta_1^k KDD_{i,t} + \beta_2^k Reform_{i,t} + \beta_3^k KDD_{i,t} \times Reform_{i,t} + \beta_4^k P_{i,t} + \beta_5^k P_{i,t}^2 + \nu_i^k + \varepsilon_{i,t}^k, \quad (5)$$

Table 1: Summary statistics at the regional level (N×T=513).

	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
Agricultural area (ha)	42,731.13	42,263.95	0.01	28,688.20	132,153.20
Arable area (ha)	22,403.71	31,904.47	0.00	5327.90	90,305.10
Regional area (ha)	164,435.29	138,392.68	4,845.34	154,056.69	484,834.61
Tractors (nb.ha)	1.82	12.47	0.00	0.32	220.00
Irrigation pumps (nb. equiments/ha)	0.19	0.29	0.00	0.10	1.68
Labor (nb. days/ha)	221.37	1,089.81	12.07	47.09	8,8865.39
Killing degree days (nb. above 28°C)	48.49	51.06	0.00	35.65	283.94
Beneficial degree days (nb. days in 0°C-28°C)	2,730.01	393,58	1,879.81	2,627.65	3,557.59
Rainfall (centimeters)	19.28	13.06	1.03	18.42	61.94
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 28°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). The statistics for labor are computed on another dataset, with data available for 2013 and 2016 only. See the text for a full description of the variables and their corresponding sources.

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), $KDD_{i,t}$ is the amount of degree days above 28°C during the growing season in t and i, $P_{i,t}$ 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),[7] ν_i^k is the region fixed effect and $\varepsilon_{i,t}^k$ is the remaining error. We estimate the parameters β_1^k to β_5^k for $k \in \{1, 2, 3\}$ using Ordinary Least Square (OLS), clustering the standard errors at the regional level to account for serial correlation. As further explained in Section 6.4, our results are also robust when additionally correcting the clusters for spatial correlation with Conley (1999)'s approach.

According to the literature (Bareille and Chakir, 2024), the obtained estimates $\hat{\beta}^k$ can be interpreted as causal impacts of contemporaneous weather conditions on yields of crop k, *net of*

[7] In line with Diao and Song (2024), Section 6.4 displays the result of some falsification tests showing that the effects of land registry manifest only two years after their introduction – formally, the effects of the reform are not distinguishable in our estimations before two years, and remain after two years. Note also that we drop from our sample the 17 regions – out of the 74 (see Section 4.1). 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 $t \in [2010 : 2019]$.

the effects of short-term adaptation.[8] The main originality of our model is that, by considering the heterogeneous conditions in both the weather and land property rights across Greece, we add a secondary to the main treatment. Indeed, while the literature assessing climate change impacts is mostly interested in obtaining weather estimates (Blanc and Schlenker, 2017; Carter et al., 2018), we seek to recover these estimates both with and without the cadastral reform. In this context, we specifically focus on the relative values of $\hat{\beta}_1^k$ and $\hat{\beta}_3^k$ – a situation where the two estimates are of the opposite (resp. same) sign would typically imply that more secured land rights offset (resp. amplify) the effects of heat on crop yields. Section 6.1 shows that the two estimates are of opposite signs for the three considered crops.

Following Aragón et al. (2021), we estimate the same types of functions than those in equation (5) but replacing crop yields $y_{i,t}^k$ as dependent variables by crop areas $a_{i,t}^k$ – for $k \in \{1, 2, 3\}$, expressed in hectare – and total inputs $x_{i,t}^l$ (for $l \in \{1, 2, 3\}$, respectively standing for the quantity of machinery, labor and irrigation per hectare). While crop yield estimates capture both the direct and indirect impacts of weather (via plant growth and adaptation respectively), those for crop areas and agricultural inputs reflect the farmers' adaptation decisions only (respectively at the extensive and intensive margins). As for crop yields, we are particularly interested in comparing the heat estimates with and without the reform (i.e., comparing the independent and interaction estimates). Sections 6.2 and 6.3 show that the two estimates are of opposite signs for crop areas, but potentially of the same signs for the agricultural inputs.

5.2 Identification strategy

Our identification strategy leverages within-sample variations in two primary treatments: heat exposure and cadastral reform. Specifically, we assess their joint impacts on crop yields, areas, and input use by comparing the effects of region-specific abnormal annual heat deviations between regions that have undergone cadastral reform and those that have not (or have yet to do so). In line with the recommended practices (Blanc and Schlenker, 2017), we identify the effects of these two treatments after controlling for unobserved regional (time-invariant) characteristics with regional fixed effects. While our preferred specification control for these time-invariant factors, we show in complamentary analyses that our results are robust to the control of potential time confounders (e.g., by adding international prices, time trends or year fixed effects).

[8]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.

Our identification relies on the assumption that climate change and land registry are both exogenous to crop yields and agricultural practices. The main concern that our analysis needs to address is whether the timing of the cadastral reform is inversely affected by climate change or agricultural outcomes. To address this, we first examine their impacts on the timing of the registry reform. Specifically, we estimate cross-sectional linear probability regressions – thus without region fixed effects – on the likelihood of receiving the land registry in each year starting in 2014, where the independent variables are temperature and precipitation during the previous growing season. For example, in the 2014 regression, temperature, precipitation, and other agricultural outcomes from 2013 were used to predict probability of each region receiving the land registry in 2014. The results, shown in Table A1 of the Supplementary Materials, reveal that agricultural and climate variables have minimal and statistically insignificant predictive power for land registry implementation in the following year.

Nevertheless, there is anecdotal evidence that the land registry was first implemented in regional units of large crop area with the intention to better regulate the direct payment received from European Common Agricultural Policy, which account for 75% of the total subsidies and 26% of the total income of the agricultural sector (Spanou 2018 , pp.107).[9] One natural concern arises that the land registry increases the agricultural subsidies in the treated regions, thereby affecting the adaptation strategies under climate change.

To address this concern, we obtain data on the amount of Common Agriculture Subsidy from 2014 to 2019 at the regional unit level from Nicholas et al. (2021). As shown in Figure A12, the total amount of agricultural subsidies received by regional units is quite stable, regardless of when they received the land registry. This is not surprise as the data from the land registry have not been used for distributing agricultural subsidies by the end of 2018.[10]

6 Results

This section first examines the impact of heat damage on crop yields conditional on whether Greek regions have received the land registry program (Section 6.1). It then investigates the effects of the land registry on farmers' adaptation strategies, focusing on both the extensive and intensive margins (Sections 6.2 and 6.3). The section ends by robustness tests (Section 6.4) and ruling out alternative mechanisms (Section 6.5).

[9] The percentages are calculated based on the agriculture statistical factsheet obtained from https://agriculture.ec.europa.eu/cap-my-country_en

[10] See OPEKE Business Plan 2019-2022, accessed on Oct 17, 2022 from https://www.eliamep.gr/wp-content/uploads/2018/11/metarrythmiseis-sth-dimosia-dioikisi-sti-diarkeia-tis-krisis.pdf

6.1 Crop yields

Columns (1) to (3) in Table 2 display our preferred estimates – those coming from the estimation of equation (5) – for wheat, barley and maize yields respectively. On the one hand, the coefficients of the number of degree days above 28°C (KDD^{28}) are negative and significant in all columns, indicating that extreme heat generally decreases crop yields. One additional degree day above 28°C at the average point typically decreases the crop yields of the three crops by about 0.1% for the regions without the land registry.[11] These results are fully in line with previous results from the literature (Schlenker and Roberts, 2009; Blanc and Schlenker, 2017; Aragón et al., 2021).

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

	Dependent variable: $log(y^k_{i,t})$		
	Wheat	**Barley**	**Maize**
KDD^{28}	-0.0013 ***	-0.0007 *	-0.0010 **
	(0.0004)	(0.0004)	(0.0005)
KDD^{28} × Registry reform	0.0018 ***	0.0015 *	0.0022 ***
	(0.0006)	(0.0008)	(0.0005)
Registry reform	-0.0941	-0.1118 *	-0.1060 **
	(0.0574)	(0.0581)	(0.0377)
Precipitation controls	Yes	Yes	Yes
Region fixed effects	Yes	Yes	Yes
χ^2 joint Student test for KDD^{28}	0.6144	0.6486	3.7956 *
χ^2 joint Wald test for registry	0.1297	1.5590	0.1730
Adj. R^2	0.6537	0.7367	0.7051
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 28°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.

On the other hand, the coefficients of killing degree days interacted with the land registry (KDD^{28} × Registry reform) are positive and significant for the three crops. The size of coefficients are actually larger than those for KDD^{28} independently. Combining the effects of KDD^{28} and KDD^{28} × Registry reform at the average point suggests that one additional degree day may increase crop yields up to 0.1% in regions covered by the land registry.[12] The joint Student test for KDD^{28} actually suggest that heat exposure has no significant effect on crop yields at the statistical

[11] In detail, a one-standard-deviation increase in heat exposure results in a decrease in wheat yields by 6.6%, barley yields by 3.6%, and maize yields by 5.1% for the regions without the land registry.

[12] In detail, a one-standard-deviation increase in heat exposure increases wheat yield by 2.5%, barley yield by 4.1%, and maize yield by 6.1% in regions covered by the land registry.

threshold of 5%. This means that the land tenure improved by the land registry program completely offsets the detrimental effects of extreme heat on crop yields. Taking the uncertainties surrounding the independent estimates and those in interactions, we find that receiving the reform offset to the very least 30%, 10% and 63% of the negative effects of abnormal heat exposure on wheat, barley and maize yields (compared to a situation where they would have not received the reform).

The above patterns provide the first evidence that improved land property rights enable farmers to better cope with harmful temperatures. These results suggest behavioral changes from the farmers, which, upon receiving received better land property rights, should have implemented different adaptation strategies to cope differently with the impacts of heat on crop yields. To gain deeper insights into changes in adaptation strategies, we examine whether extreme heat has differential impacts on agricultural inputs and areas after the land registry reform.

6.2 Crop areas

Columns (1) to (3) of Table 3 respectively report the estimates of the heat impacts on wheat, barley ad maize areas. On the one hand, the coefficients of the number of degree days above 28 °C are positive and significant for barley and maize areas. One additional degree days above 28°C encourage farmers without the registry to enlarge their cropping area from 0.2% to 0.4% in the regions without the land registry.[13] These results indicate that farmers with poor land property rights cope with heat by enlarging crop areas, which is consistent with previous finding in Peru (Aragón et al. 2021).

On the other hand, the coefficients of the number of killing degree days above 28 °C interacted with the land registry are negative and significant for barley and maize areas. Combining the effects of KDD^{28} and KDD^{28} × Registry reform at the average point suggests that one additional degree days encourage farmers with the registry to only enlarge their cropping area by maximum 0.1%.[14] Compared to regions without land registry, the improved tenure security offset the effects of heat on crop areas by 70% to 95% at the average point (up to 160% for wheat, but results are not significant). Actually, the joint Student test for KDD^{28} actually suggest that heat exposure has no significant effect on crop areas for any of three crops. This means that that farmers lacking tenure security adopt land-extensification strategies, expanding crop areas to cope with extreme

[13] In details, a one-standard-deviation increase in the number of Killing degree days results in an increase in wheat area by 7.7%, barley area by 17.9%, and maize yield by 19.4% in the regions without the land registry.

[14] A one-standard-deviation increase in the number of Killing degree days results in a decrease in wheat area by 4.6%, an increase in barley area by 5.6%, and an increase in maize area by 1.5%.

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^{28}	0.0015	0.0035 ***	0.0038 ***
	(0.0021)	(0.0010)	(0.0010)
KDD^{28} × Registry reform	-0.0024 *	-0.0024 **	-0.0035 **
	(0.0013)	(0.0012)	(0.0015)
Registry reform	-0.0847	0.2054	-0.2184
	(0.1056)	(0.1277)	(0.1703)
Precipitation controls	Yes	Yes	Yes
Region fixed effects	Yes	Yes	Yes
χ^2 joint Student test for KDD^{28}	0.45758	1.7196	0.0470
χ^2 joint Wald test for registry	11.0520 ***	0.9462	7.0201 ***
Adj. R^2	0.9082	0.8767	0.9502
Observations	513	513	513

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 28°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.

heat, whereas farmers with tenure security do not. Next Section investigates whether these latter farmers adapt along alternative strategies.

6.3 Agricultural inputs

Columns (1) to (3) of Table 4 respectively report the estimates of the heat impacts on the number of tractors, labor working hours and irrigation equipments (the dependent variables are normalized by the amount of agricultural area). On the one hand, the coefficients of the number of degree days above 28 °C are either negative or not significantly different from zero in all columns, indicating that farmers facing higher heat exposure do not increase agricultural inputs when they lack tenure security. One additional degree day typically encourage farmers at the average point to reduce their number of tractors by 0.2%, without providing significant incentives to adapt along labor or irrigation adjustments.

On the other hand, the coefficients of killing degree days interacted with the land registry are positive and significant in all three columns. Combining the effects of KDD^{28} and KDD^{28} × Registry reform at the average point suggests that one additional degree days encourage farmers with the registry to increase their use of irrigation and labor by 0.2% and 1.1% respectively (while the use of tractor would increase by less than 0.1% at the average point). The joint Compared to

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

	Dependent variable: $log((1+x^k_{i,t})/A_{i,t})$		
	Machinery	**Labor**	**Irrigation**
KDD^{28}	-0.0022 **	0.0017	0.0002
	(0.0010)	(0.0022)	(0.0007)
KDD^{28} × Registry reform	0.0026 **	0.0056 ***	0.0017 **
	(0.0010)	(0.0009)	(0.0008)
Registry reform	-0.1917 **	-0.4960 ***	-0.2441
	(0.0879)	(0.0968)	(0.1603)
Precipitation controls	Yes	Yes	Yes
Region fixed effects	Yes	Yes	Yes
χ^2 joint Student test for KDD^{28}	0.31933	9.6877 ***	8.4727 ***
χ^2 joint Wald test for registry	2.2898	11.9547 ***	1.4172
R^2	0.6483	0.9297	0.6826
Observations	511	76	454

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 input considered. Machinery is measured with the number of tractors per hectare of the whole regional agricultural area (minus fallows). Labor is measured as the number of total workdays (employee and permanent labor) per hectare of the whole regional agricultural area (minus fallows). Irrigation is measured with the number of water pumps per hectare of the whole regional agricultural area (minus fallows). Killing degree days are measured as the cumulative days spent above 28°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.

regions without a land registry, these results thus indicate that improved tenure security reverses the effects of heat on the number of tractors and significantly amplifies its impact on labor hours and irrigation equipment – that is, that farmers with complete tenure security adopt land-intensification strategies, increasing both capital and labor to cope with extreme heat. Looking complementarily at Table 2 suggest that these land-intensification adaptation strategies to cope with higher heat exposure ultimately results in lower heat damage to crop yields. Together with Table 3, this further means that receiving better land property rights encourage farmers to reduce heat damage on crop yields by switching from land-extensification to land-intensification adaptation strategies.

6.4 Sensitivity analyses

The results above show that farmers receiving the cadastral reform adjust their heat adaptation strategies by switching 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. To test the robustness of the results, we re-estimate our benchmark equations above with alternative empirical choices regarding (i) the transformation of our outcome variables (either using inverse hyperbolic sine transformation or alternative approach proposed by Chen and Roth 2024), (ii) the definition of heat exposure (either using larger thresholds or extended definition of the growing season), (iii) the time structure of the error terms (controlling for prices, trends or year fixed effects), (iv) the correction of our standard errors for spatial correlation using Conley (1999) (with distance thresholds up to 500 km) and (v) the use of alternative definitions for the registry treatment (where the arbitrarily shift the timing of the reform). Discussed in detailed in Appendix A4 of the Supplementary Materials, we show that our preferred results are overall robust to all of these changes. This is particularly true regarding our estimates for input use (machinery, labor and irrigation), for which all of the estimated interaction terms between heat and land registry remain statistically significant in all these complementary analyses.

6.5 Ruling out alternative mechanisms

We interpreted our previous results as if farmers respond to heat by either adjusting their crop lands or agricultural inputs. This explanation could however be threatened by possible intermediate mechanisms that would indirectly affect these outcomes – thus collapsing our previous interpretations. We explore some of these possible alternative mechanisms below, regressing several alternative outcome variables in our preferred setting – as described in equation (5).

Adjustments of other areas. The interpretation of our previous results could be threatened by the fact that farmers shift their heat-induced changes in crop allocation for other agricultural outputs, which contaminate by construction crop areas. Table A6 in Supplementary Materials does not support this narrative. Formally, we find that farmers expand their total area in response to heat (as for particular crops considered in Table 3), but that receiving the reform does not shift this pattern. Including vineyards and orchards, permanent crop areas are orthogonal to heat exposure, whether with or without land registry (reflecting hereby the fixity of these areas to short-term shocks). Finally, while farmers adjust to heat by enlarging fallow areas, Table 3 indicates that farmers do not adjust differently with or without the reform.

Fires. Diao and Song (2024) showed that one of the main effect of the Greek cadastral reform relates to fire reduction in the country (in particular those from agricultural sources). This effect could threaten our previous interpretations since burnt areas can latter affect agricultural productivity (Abdulai and Binder, 2006). Table A7 in Supplementary Materials does not support this narrative. Indeed, while we confirm that having received the reform strongly reduce burnt areas in agricultural areas (but not on forest and urban areas), the interaction between heat and the reform is always insignificant. That is, fires could not act as a confounding mechanism in our preferred analyses.

Livestock. Farmers do not only grew crops, but also raise livestock. Livestock are interesting for at least three reasons in our study. In the one hand, livestock is commonly considered as assets that can be sold to soften the negative effects of a shock (Fafchamps et al., 1998). In the other hand, some (but not all) livestock are grazing animals that eat grass and other forages, such that some breeding activities may be negatively affected by higher heat exposure (Lin et al., 2023). Third, breeding animals generate organic wastes that could be used to fertilize crops (Shi et al., 2024).

Table A8 in Supplementary Materials yet shows that livestock density is orthogonal to both land registry and heat exposure. In particular, none of the interaction parameter between the two significantly affect the density of pigs, sheeps, goats or cows. That is, changes in breeding activities could not threaten our previous interpretation that farmers reduce heat damage on crop yields after receiving the reform by switching from land-extensification to land-intensification adaptation strategies.

7 Conclusion

This paper exploits the recent "Hellenic Cadastre" roll-out program having took place in Greece to show how the quality of land property rights affect the extent of heat damage on agriculture by shaping farmers' incentives to adapt. Consistently with our theoretical framework, we empirically show that farmers receiving more secured land property rights rationally shift from land-extensification to land-intensification adaptation strategies in response to higher heat exposure. While the latter mean that farmers respond to heat by expanding croplands, the former mean that they respond by intensifying their use of machinery, labor and irrigation, ultimately allowing them to offset most of the heat-induced yield losses.

Beyond its implications for Greek agriculture, this research underscores the broader relevance of complete land property rights in fostering resilience to climate change. As global warming continues to intensify, our results show that strengthening land institutions may offer a viable path to safeguarding agricultural productivity and supporting global food security. While Greece's intermediate position between developing and developed countries provides unique insights, future research could explore the interplay between land property rights and adaptation in (less developed) countries with more limited access to agricultural inputs.

References

Abdulai, A. and Binder, C. R. (2006). Slash-and-burn cultivation practice and agricultural input demand and output supply. *Environment and Development Economics*, 11(2):201–220.

Acemoglu, D., Naidu, S., Restrepo, P., and Robinson, J. A. (2019). Democracy does cause growth. *Journal of Political Economy*, 127(1):47–100.

Adamopoulos, T., Brandt, L., Chen, C., Restuccia, D., and Wei, X. (2024). Land security and mobility frictions. *Quarterly Journal of Economics*.

Adamopoulos, T. and Restuccia, D. (2020). Land reform and productivity: A quantitative analysis with micro data. *American Economic Journal: Macroeconomics*, 12(3):1–39.

Allen, D. W. (2002). The rhino's horn: incomplete property rights and the optimal value of an asset. *The Journal of Legal Studies*, 31(S2):S339–S358.

Amare, M. and Balana, B. (2023). Climate change, income sources, crop mix, and input use decisions: Evidence from Nigeria. *Ecological Economics*, 211:107892.

Aragón, F. M., Oteiza, F., and Rud, J. P. (2021). Climate change and agriculture: Subsistence farmers' response to extreme heat. *American Economic Journal: Economic Policy*, 13(1):1–35.

Auffhammer, M., Hsiang, S. M., Schlenker, W., and Sobel, A. (2013). Using weather data and climate model output in economic analyses of climate change. *Review of Environmental Economics and Policy*.

Balla, E., Zevenbergen, J., Madureira, A. M., and Georgiadou, Y. (2022). Too much, too soon? The changes in Greece's land administration organizations during the economic crisis period 2009 to 2018. *Land*, 11(9):1564.

Bareille, F. and Chakir, R. (2024). Structural identification of weather impacts on crop yields: Disentangling agronomic from adaptation effects. *American Journal of Agricultural Economics*, 106(3):989–1019.

Bezabih, M., Di Falco, S., Mekonnen, A., and Kohlin, G. (2021). Land rights and the economic impacts of climatic anomalies on agriculture: evidence from Ethiopia. *Environment and Development Economics*, 26(5-6):632–656.

Blanc, E. and Schlenker, W. (2017). The use of panel models in assessments of climate impacts on agriculture. *Review of Environmental Economics and Policy.*

Burke, M. and Emerick, K. (2016). Adaptation to climate change: Evidence from US agriculture. *American Economic Journal: Economic Policy*, 8(3):106–40.

Carter, C., Cui, X., Ghanem, D., and Mérel, P. (2018). Identifying the economic impacts of climate change on agriculture. *Annual Review of Resource Economics*, 10:361–380.

Chari, A., Liu, E. M., Wang, S.-Y., and Wang, Y. (2021). Property rights, land misallocation, and agricultural efficiency in China. *The Review of Economic Studies*, 88(4):1831–1862.

Chen, C., Restuccia, D., and Santaeulàlia-Llopis, R. (2022). The effects of land markets on resource allocation and agricultural productivity. *Review of Economic Dynamics*, 45:41–54.

Chen, J. and Roth, J. (2024). Logs with zeros? some problems and solutions. *The Quarterly Journal of Economics*, 139(2):891–936.

Chen, S. and Gong, B. (2021). Response and adaptation of agriculture to climate change: Evidence from China. *Journal of Development Economics*, 148:102557.

Coase, R. H. (1960). The problem of social cost. *Journal of Law and Economics*, 3(1):1–28.

Conley, T. G. (1999). GMM estimation with cross sectional dependence. *Journal of Econometrics*, 92(1):1–45.

Cui, X. (2020). Beyond yield response: weather shocks and crop abandonment. *Journal of the Association of Environmental and Resource Economists*, 7(5):901–932.

Cui, X. and Xie, W. (2022). Adapting agriculture to climate change through growing season adjustments: Evidence from corn in China. *American Journal of Agricultural Economics*, 104(1):249–272.

D'Arcy, M., Nistotskaya, M., and Olsson, O. (2024). Cadasters and economic growth: A long-run cross-country panel. *Journal of Political Economy*, In press.

Diao, L. and Song, H. (2024). Does improved tenure security reduce fires? Evidence from the Greece land registry. *Journal of Environmental Economics and Management*, 127:103002.

Eurostat (2011). Agriculture, forestry and fishery statistics — 2010 edition. Technical report, Eurostat.

Fafchamps, M., Udry, C., and Czukas, K. (1998). Drought and saving in west africa: are livestock a buffer stock? *Journal of Development economics*, 55(2):273–305.

Fisher, A. C., Hanemann, W. M., Roberts, M. J., and Schlenker, W. (2012). The economic impacts of climate change: evidence from agricultural output and random fluctuations in weather: comment. *American Economic Review*, 102(7):3749–60.

Founda, D., Katavoutas, G., Pierros, F., and Mihalopoulos, N. (2022). The extreme heat wave of summer 2021 in athens (greece): cumulative heat and exposure to heat stress. *Sustainability*, 14(13):7766.

Gammans, M., Mérel, P., and Ortiz-Bobea, A. (2017). Negative impacts of climate change on cereal yields: statistical evidence from France. *Environmental Research Letters*, 12(5):054007.

Georgopoulou, E., Gakis, N., Kapetanakis, D., Voloudakis, D., Markaki, M., Sarafidis, Y., Lalas, D. P., Laliotis, G. P., Akamati, K., Bizelis, I., et al. (2024). Climate change risks for the mediterranean agri-food sector: The case of greece. *Agriculture*, 14(5):770.

He, X. and Chen, Z. (2022). Weather, cropland expansion, and deforestation in Ethiopia. *Journal of Environmental Economics and Management*, 111:102586.

Henry, L. (2022). Adapting the designated area of geographical indications to climate change. *American Journal of Agricultural Economics*, page Forthcoming.

IPCC (2022). Climate change 2022: Impacts, adaptation and vulnerability. contribution of working group ii to the sixth assessment report of the intergovernmental panel on climate change. Cambridge university press. cam, [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)].

Jagnani, M., Barrett, C. B., Liu, Y., and You, L. (2021). Within-season producer response to warmer temperatures: Defensive investments by Kenyan farmers. *Economic Journal*, 131(633):392–419.

Ji, X. and Cobourn, K. M. (2021). Weather fluctuations, expectation formation, and short-run behavioral responses to climate change. *Environmental and Resource Economics*, 78:77–119.

Libecap, G. D. and Lueck, D. (2011). The demarcation of land and the role of coordinating property institutions. *Journal of Political Economy*, 119(3):426–467.

Lin, Z., Ortiz-Bobea, A., Wolf, C. A., and Reed, K. F. (2023). Extreme weather impacts on US dairy production: Evidence from 8 million cows. Technical report, Working Paper, Cornell University.

Lobell, D. B., Hammer, G. L., McLean, G., Messina, C., Roberts, M. J., and Schlenker, W. (2013). The critical role of extreme heat for maize production in the United States. *Nature Climate Change*, 3(5):497–501.

Lobell, D. B., Schlenker, W., and Costa-Roberts, J. (2011). Climate trends and global crop production since 1980. *Science*, 333(6042):616–620.

Mérel, P. and Gammans, M. (2021). Climate econometrics: Can the panel approach account for long-run adaptation? *American Journal of Agricultural Economics*, 103(4):1207–1238.

Murken, L., Mager, G., Laudien, R., Kraehnert, K., and Gornott, C. (2024). The impact of weather risk on tenure security: Evidence from smallholder farmers in tanzania. *Land Economics*.

Nicholas, K. A., Villemoes, F., Lehsten, E. A., Brady, M. V., and Scown, M. W. (2021). A harmonized and spatially explicit dataset from 16 million payments from the European Union's Common Agricultural Policy for 2015. *Patterns*, 2(4):100236.

Papakostas, A. (2018). Building state infrastructural capacities: Sweden and Greece. In *Bureaucracy and Society in Transition*, volume 33, pages 39–67. Emerald Publishing Limited.

Rokos, D. (2018). Recent developments in the context of the Hellenic Cadastre. *Proceedings of the Tufe2018-Economy, Society and Climate Change–The impact of mega trends in the Built Environment, Construction Industry and Real Estate, Athens, Greece*, pages 7–10.

Schlenker, W. and Roberts, M. J. (2009). Nonlinear temperature effects indicate severe damages to US crop yields under climate change. *Proceedings of the National Academy of Sciences*, 106(37):15594–15598.

Shi, T.-S., Collins, S. L., Yu, K., Peñuelas, J., Sardans, J., Li, H., and Ye, J.-S. (2024). A global meta-analysis on the effects of organic and inorganic fertilization on grasslands and croplands. *Nature Communications*, 15(1):3411.

Spanou, C. (2018). Reforms in Public Administration under the crisis: Overview, Description, Evaluation. *Greek & European Economy Observatory*.

Tsigarida, A. (2019). *Evolution of the Cadastral System in Greece: Investigation of Attitudesand Perceptions of Citizens*. PhD thesis, Hellenic Open University.

Wing, I. S., De Cian, E., and Mistry, M. N. (2021). Global vulnerability of crop yields to climate change. *Journal of Environmental Economics and Management*, 109:102462.

World Bank (2019). Doing business in the European Union 2020: Greece, Ireland and Italy.

Supplementary Materials

NOTE. The material contained herein is supplementary to the article entitled "Adapting to climate change with (in)complete land property rights: Evidence from the Greece Land Registry Reform".

A1 Additional figure for the theoretical analysis

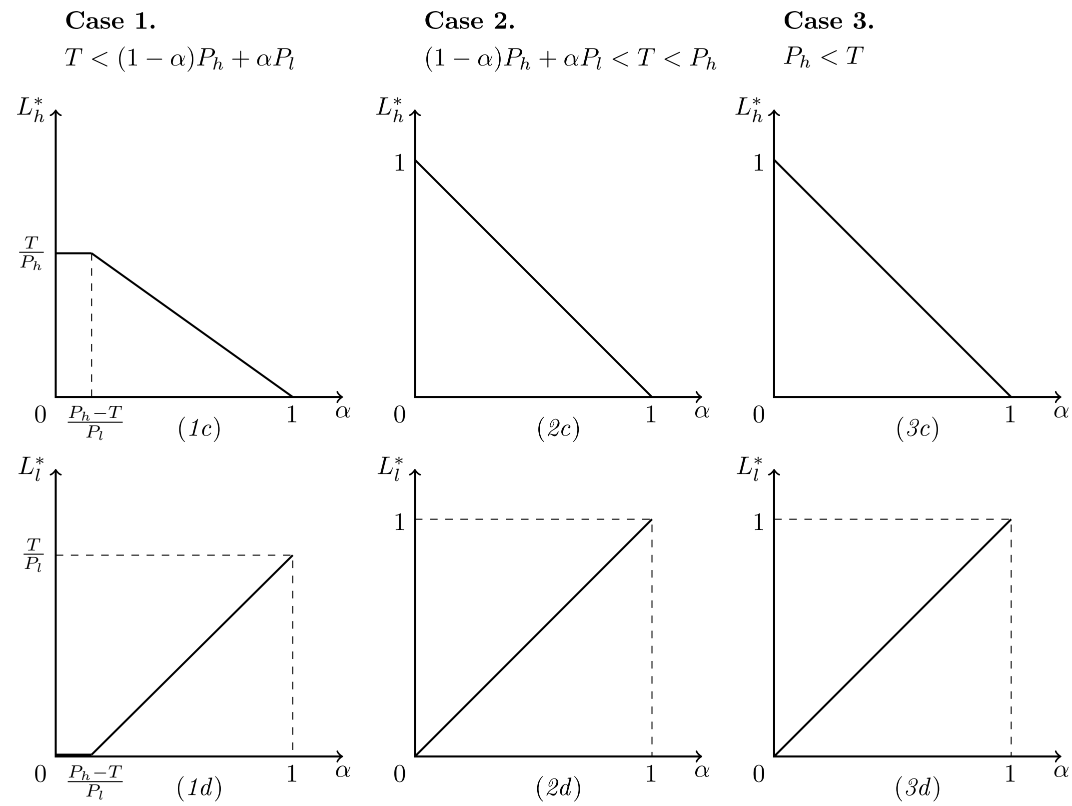


Figure A1: Farmer' adaptation strategies depending on land property rights

NOTE. The figure displays the farmer's optimal responses to higher heat exposure depending on the extent of land property rights. The figure is divided into three columns, (i) the leftest-hand column reflecting the "insecure tenure" case, (ii) the rightest-hand column reflecting the "secure tenure" case and (iii) those in the middle reflecting an intermediate case. The farmer's adaptation responses at the extensive margin are split into lands of low and high quality. Determined analytically within the Section, the relations depicted into each sub-figure can be compared one to another.

A2 Additional maps

Figure A2 displays the year of start or the land registry program recovered from the Hellenic Cadaster website. This information is then aggregated at the regional level to create our treatment variable about the presence of the land registry in the region (see Figure 2 of the main text). Figure A3 shows the spatial distribution of the trends of changes in our first treatment variables (i.e., heat exposure) across Greece. Figure 2 in the main text shows similar pattern for our second treatment variable (the year of start of the land registry reform). Figures A4 to **??** show similar changes in our outcome variables (i.e., crop yields and areas for wheat, barley and maize).

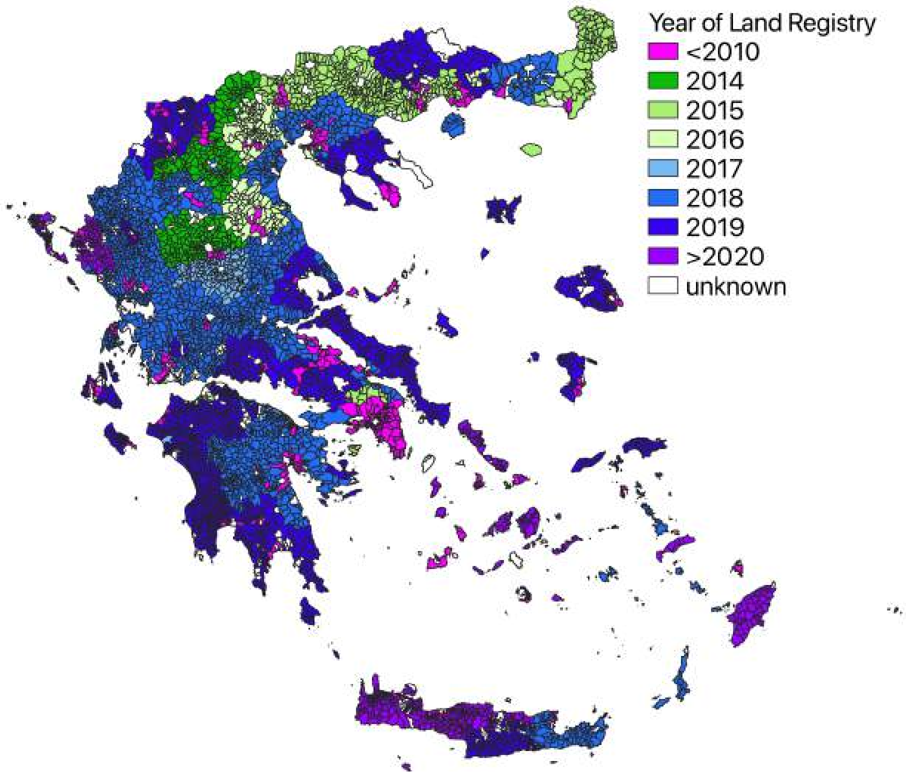


Figure A2: Year of Land Registry at the Regional Unit Level

NOTE. This figure illustrates the year in which each of the Greek municipalities began implementing the Hellenic Cadastre program. Municipalities are colored based on their first year of program initiation, as recovered from the Hellenic Cadaster website.

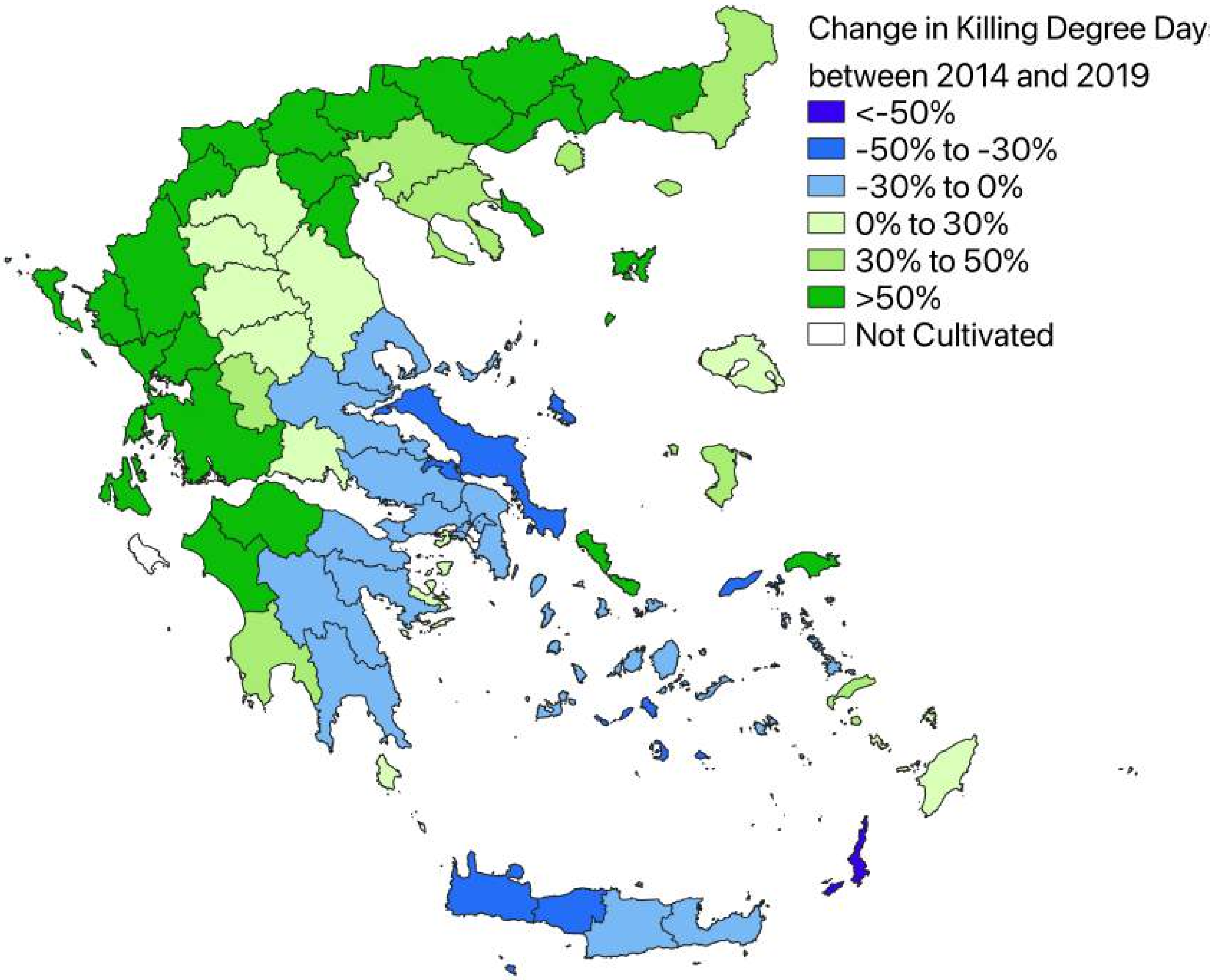
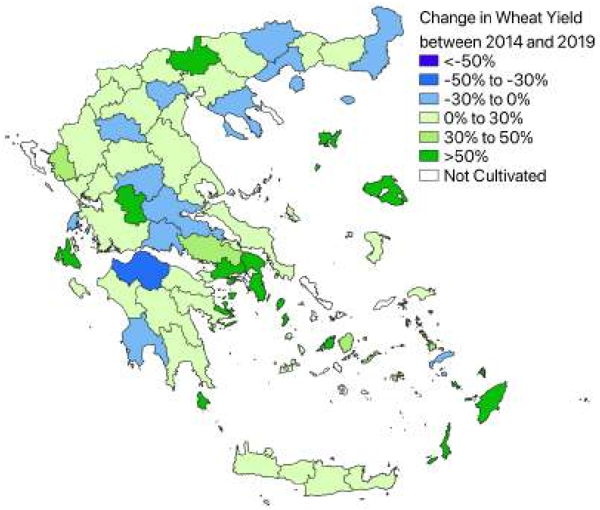
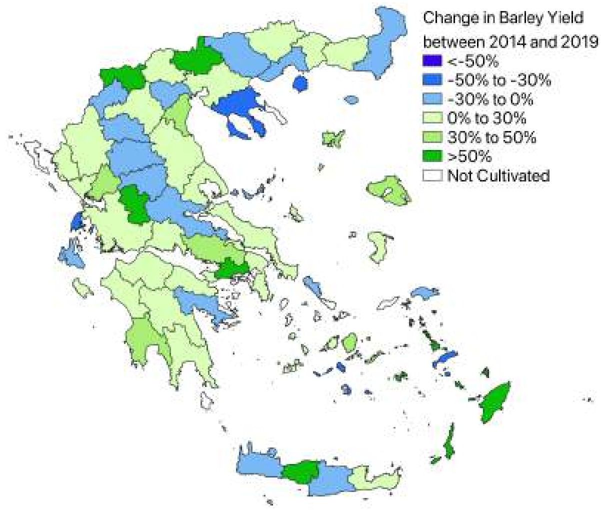


Figure A3: Percentage Change in the number of Killing Degree Days between 2014 and 2019.

a) Wheat Yield



b) Barley Yield



c) Maize Yield

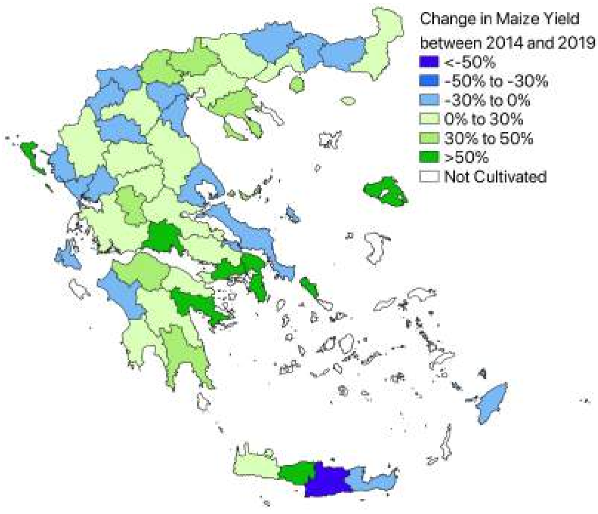


Figure A4: Percentage Change in Crop Yields between 2014 and 2019.

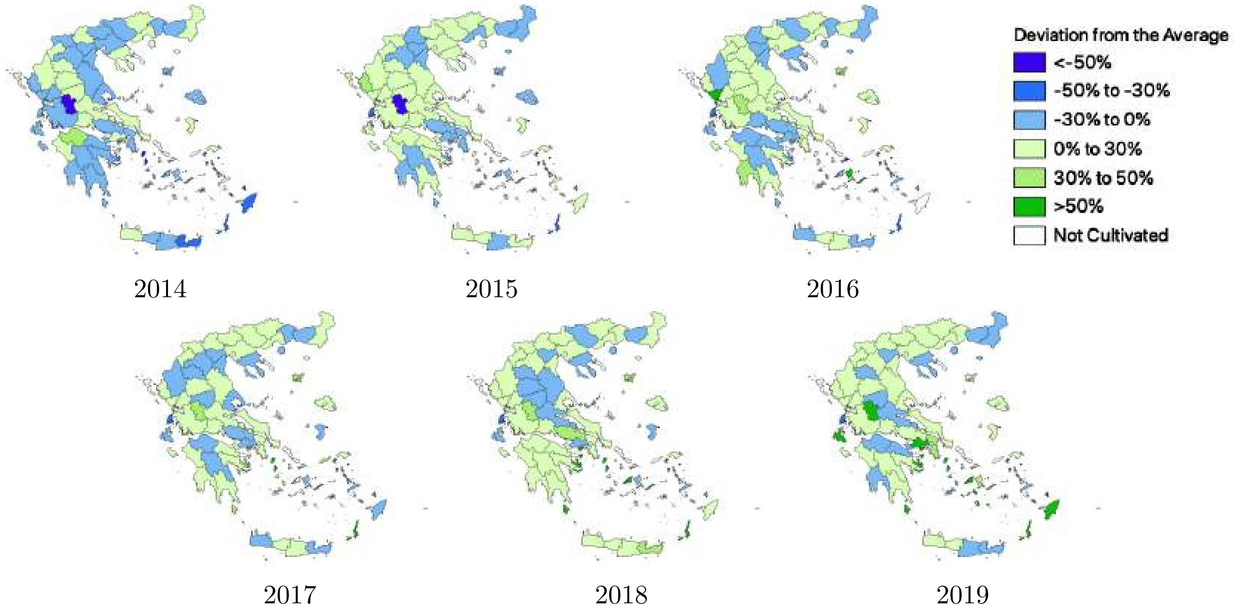


Figure A5: Percentage change in the wheat yield by year

Note: The Figure displays annual deviations of wheat yield from the regional long-term averages over the 2011-2019 period.

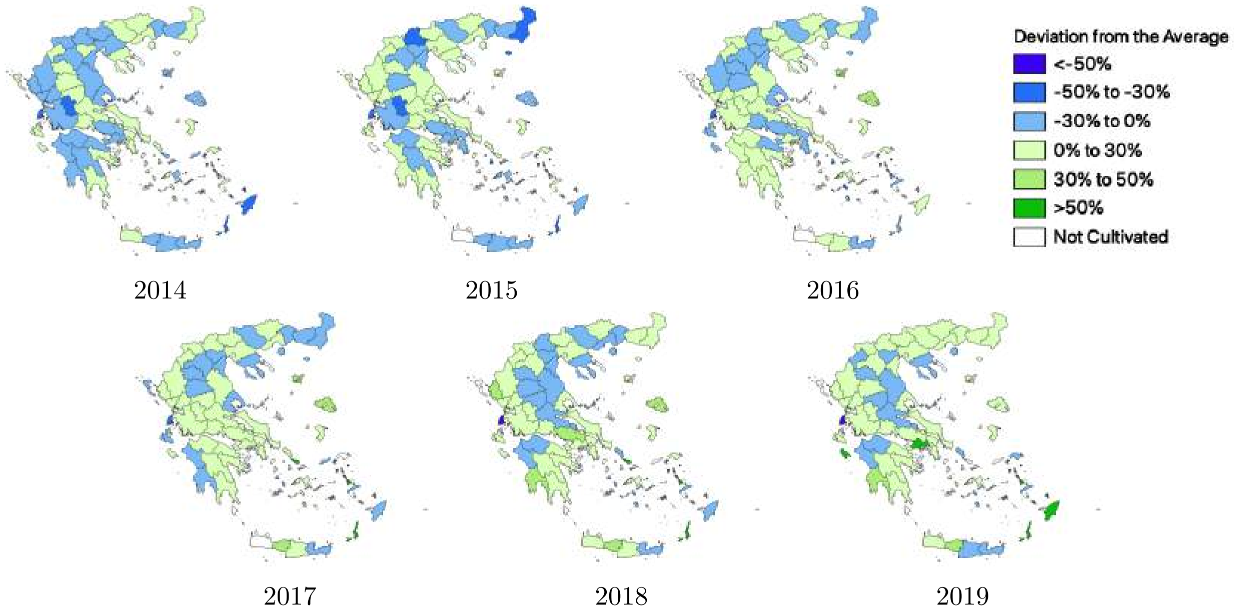


Figure A6: Percentage change in the barley yield by year

Note: The Figure displays annual deviations of barley yield from the regional long-term averages over the 2011-2019 period.

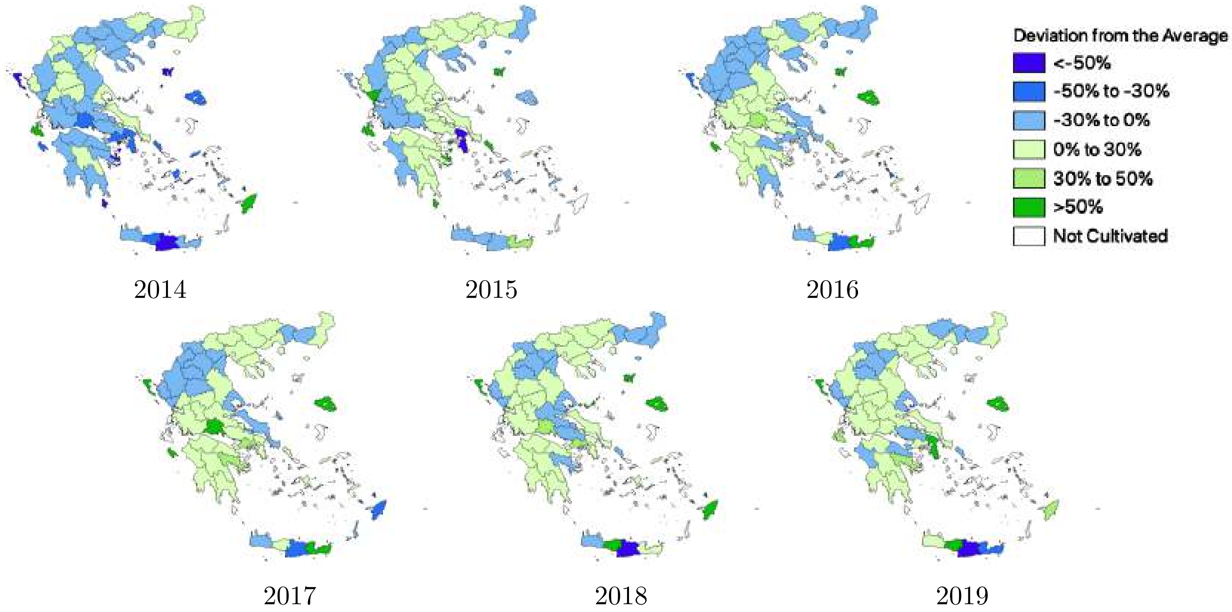


Figure A7: Percentage change in the maize yield by year

Note: The Figure displays annual deviations of maize yield from the regional long-term averages over the 2011-2019 period.

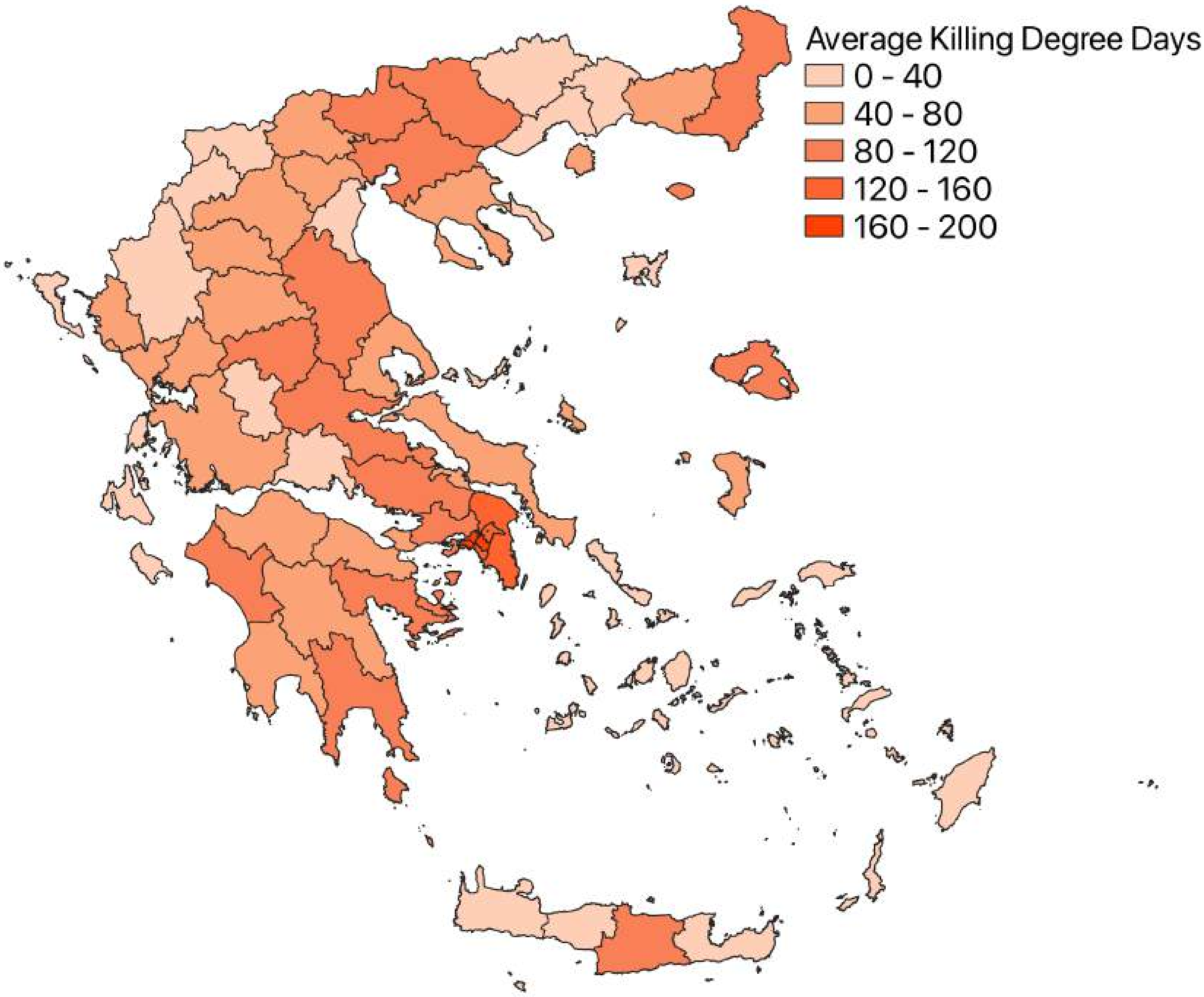


Figure A8: Long Term Average of Killing Degree Days above 28°C from 2011 to 2019.

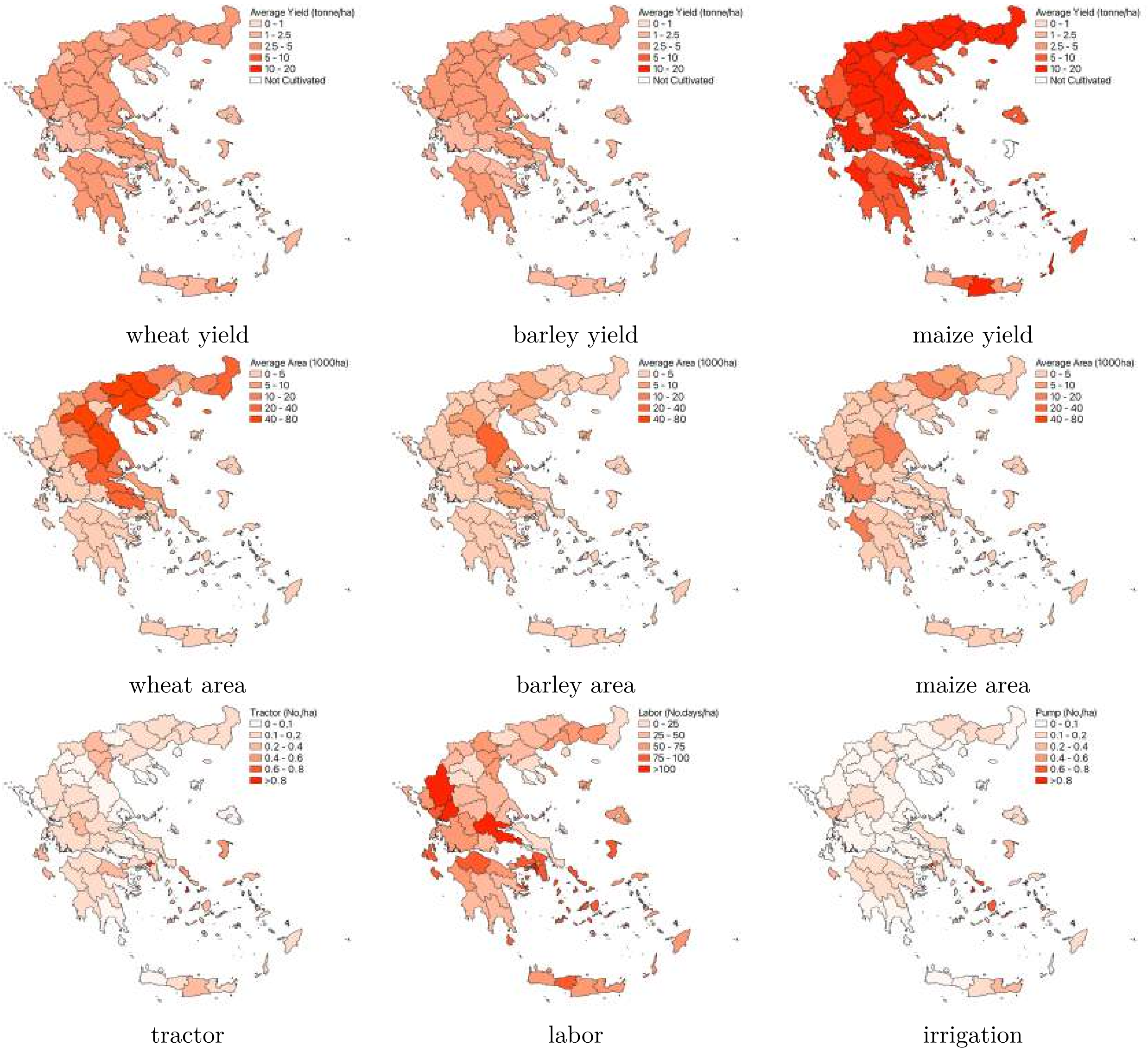


Figure A9: Long Term Average

Notes: The figure presents the long-term average of crop yields, cultivated areas, and agricultural inputs from 2011 to 2019. Due to data limitations, labor is represented by the average total working hours per hectare in 2013 and 2016.

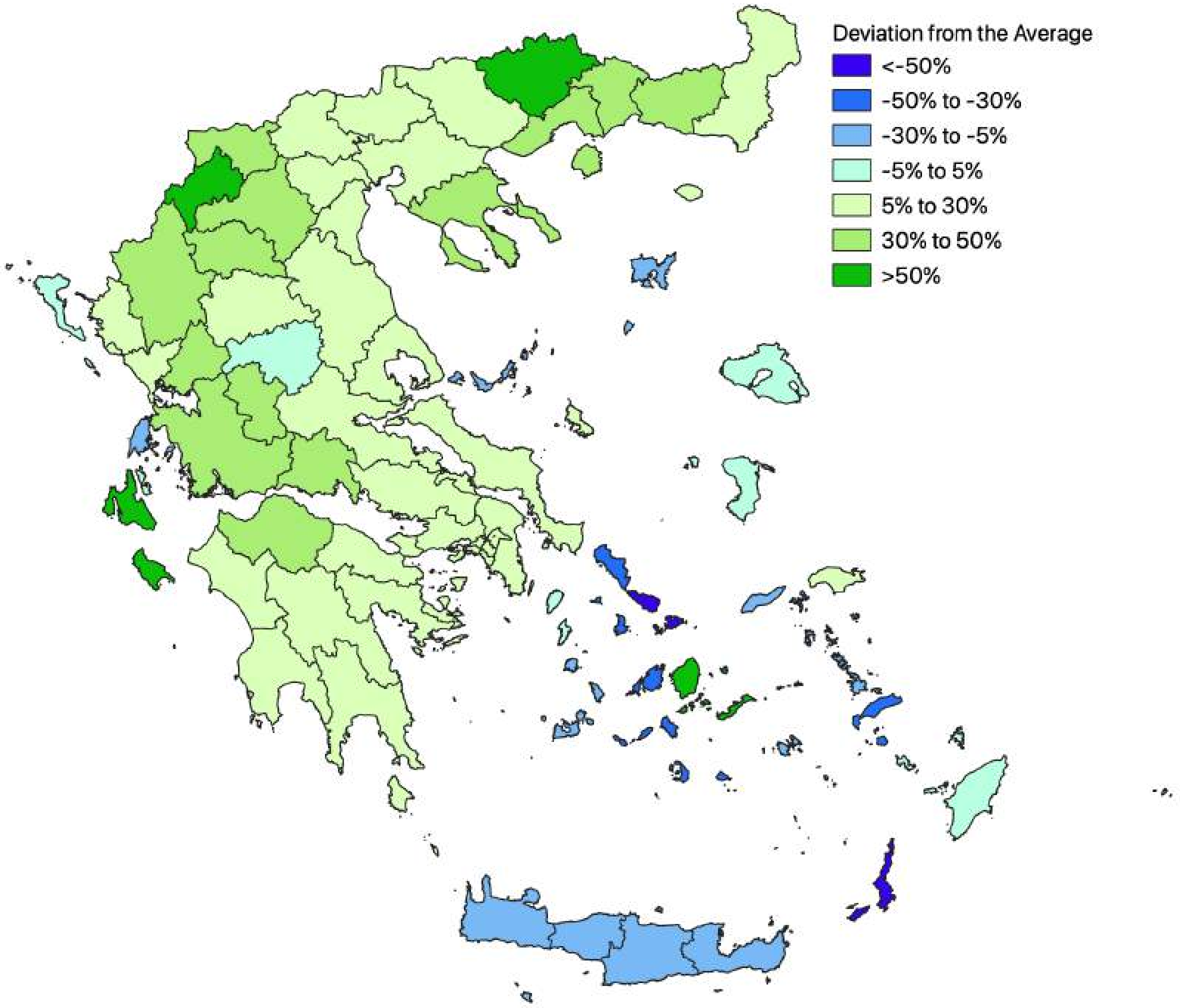


Figure A10: Deviation from the long-term average for the number of killing degree days 28°C in 2017

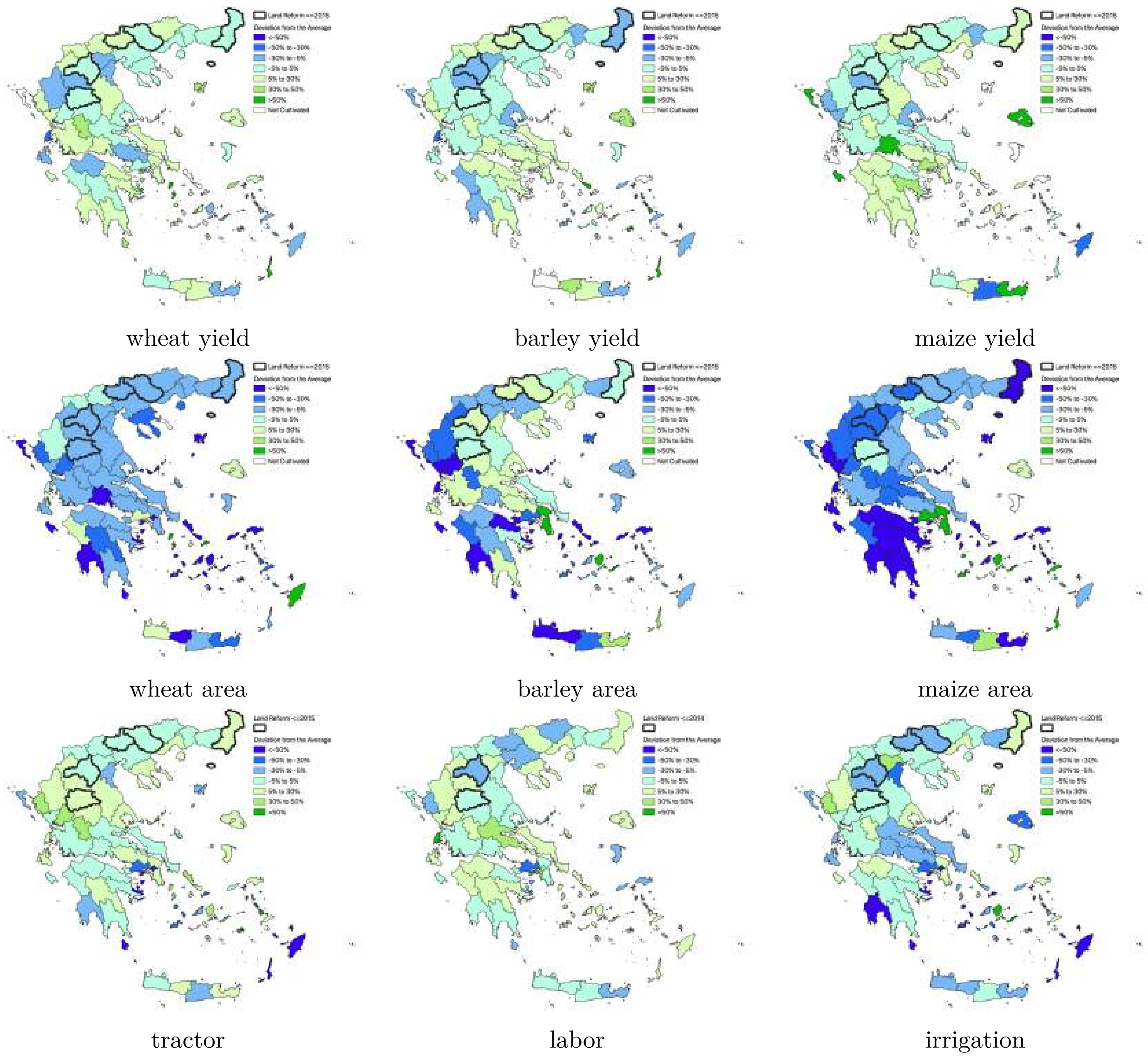


Figure A11: Deviation in 2017 from the Long Term Average

Notes: The figure shows deviations from the long-term average for crop yields, cultivated areas, and agricultural inputs in 2017. Regions marked with bold borders implemented land reform two years prior to 2017. Due to data limitations, the labor figures reflect deviations in 2016, with bold-bordered regions indicating where land reform was implemented two years before 2016.

A3 Balance test for climate

To test the exogeneity of climate variables relative to the timing of the registry reform, we perform a balance test using cross-sectional linear probability regressions. Specifically, we estimate the likelihood of a region receiving the land registry in a given year as a function of climate conditions—temperature and precipitation—during the preceding growing season (April 1 to August 31). For instance, in the regression for 2014, climate and agricultural data from 2013 is used as the independent variable to predict registry implementation. This approach, which excludes region fixed effects, allows us to assess whether agroclimatic conditions significantly influenced the timing of cadastral reform. The results, presented in Table A1, indicate that neither heat nor precipitation exhibit statistically significant predictive power across the years tested. Although some agricultural indicators significantly influenced land reform in certain years, none of these factors consistently predict outcomes over time. This evidence supports the assumption that agricultural and climate variables are exogenous to the timing of land registry implementation.

Table A1: Balance Test before Cadastral Reform

Dependent Variable:	Probability of Land Reform in Year					
	2014	2015	2016	2017	2018	2019
KDD^{28}	-.00106	.00336**	.00168	.00342	.0063	.0034
	(.00218)	(.00159)	(.00197)	(.00225)	(.00658)	(.00822)
Precipitation	.196	-.172	.172	.086	-.0788	-.22
	(.26)	(.191)	(.185)	(.212)	(.591)	(.897)
Precipitation^2	-.088	.0514	-.0622	-.0496	.0912	.0919
	(.075)	(.0564)	(.0556)	(.0643)	(.181)	(.304)
Wheat Yield	1	.27	.289	.602	2.34	5.28
	(.933)	(.698)	(.729)	(.825)	(2.32)	(3.02)
Maize Yield	.176	-.236	-.259*	-.0217	-.236	1.12
	(.195)	(.143)	(.149)	(.178)	(.496)	(.662)
Barley Yield	.499	-.442	1.82*	.416	-.829	-9.41
	(1.13)	(.814)	(1.04)	(1.25)	(3.48)	(5.16)
Wheat Area	3.86e-07	1.34e-06***	-8.02e-08	9.17e-07*	2.00e-06	2.31e-06
	(3.76e-07)	(2.77e-07)	(4.26e-07)	(4.81e-07)	(1.44e-06)	(2.13e-06)
Barley Area	-8.35e-07	-4.97e-07	-1.16e-06	-1.75e-06	-1.96e-06	5.45e-06
	(2.02e-06)	(1.49e-06)	(1.42e-06)	(1.62e-06)	(4.62e-06)	(4.89e-06)
Maize Area	1.68e-06	9.53e-07	1.55e-06	1.67e-06	-1.59e-06	-6.97e-06
	(9.94e-07)	(7.84e-07)	(1.03e-06)	(1.22e-06)	(3.52e-06)	(5.20e-06)
Non Fallow Agri. Area	-2.17e-07	-6.47e-08	-3.57e-07	-4.98e-07*	-1.14e-06	-9.96e-07
	(3.01e-07)	(2.23e-07)	(2.43e-07)	(2.86e-07)	(8.48e-07)	(1.31e-06)
Machinery	-.0000149	8.25e-06	.0000281**	-6.09e-06	.0000416	.0000454
	(.0000157)	(.0000115)	(.000011)	(.000014)	(.0000391)	(.0000644)
Irrigation	-5.48e-06	-.0000221*	-.0000319***	7.08e-06	.0000254	.0000893
	(.000015)	(.0000109)	(.0000111)	(.0000146)	(.0000407)	(.0000814)
Adj. R^2	0.00	0.66	0.21	0.02	0.08	0.04
Observations	41	39	36	35	34	22

NOTE. Samples are all regional units without cadastral reform by 2014 in column 1; 2015 in column 2; 2016 in column 3; 2017 in column 4; 2018 in column 5; and 2019 in column 6. For each column, the sample covers all regions that has not received the land registry by that year. The dependent variable is a dummy indicator that equals one if the regional units start the cadastral reform in that year. Killing degree days are measured as the cumulative days spent above 28°C between April 1st to August 31th. Precipitation are measured as the total precipitation between April 1st to August 31th. Non Fallow Agri. Area is regional agricultural area excluding fallow land. Machinery is measured with the number of tractors. Irrigation is measured with the number of water pumps.

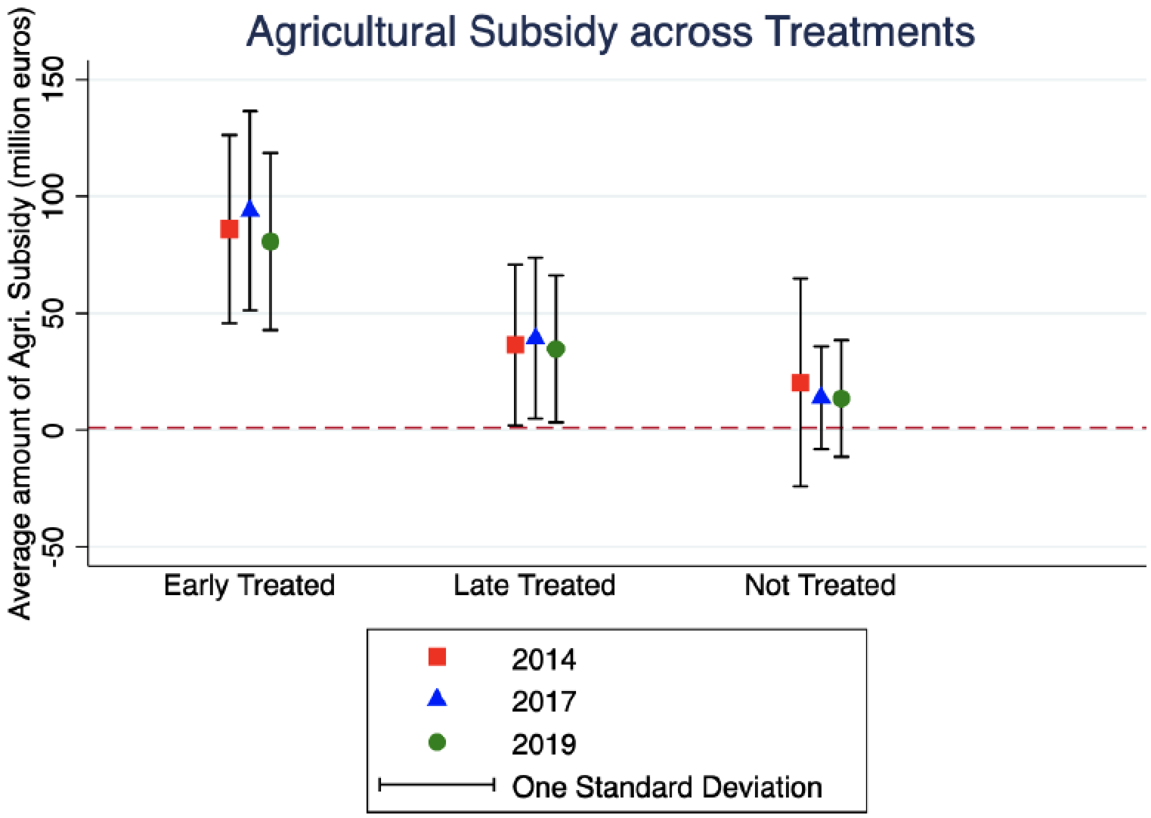


Figure A12: Agricultural Subsidy across Treatments
Note: Early treated are regional units that receive the land registry in and before 2016. Late treated are regional units that receive the land registry in and after 2017. Not treated are regional units that do not receive the land registry between 2014 and 2019.

A4 Sensitivity analyses

This appendix displays the results of our sensitivity analyses regarding the impacts of heat on crop yields, areas and input use for Greek regions with and without the land registry. We present them in details below.

Heat measurements. The way of measuring heat can ultimately influence the estimates (Blanc and Schlenker, 2017). Our main analyses consider that within-season temperature is beneficial to agriculture up to 28°C, threshold above which additional temperature negatively affect crop yields. This threshold is quite standard in the literature (e.g., it is also used by Burke and Emerick, 2016, in the US context), that push in favor of using threshold around 30°C (Schlenker and Roberts, 2009; Blanc and Schlenker, 2017). Yet, other studies have used higher threshold (e.g., Aragón et al., 2021). To test the robustness of our results to the use of alternative thresholds, we re-run our analyses using measurements of heat as cumulative temperature above 30, 32 or 34°C respectively. Table A2 displays the results of our sensitivity analyses regarding these alternative measurements. It also displays the results with heat measurements over the whole year instead of heat within the growing season only (defined from April 1 to August 30).

Table A2 shows that about all of our results are robust to these alternative heat measurements, whether it regards heat impacts on crop yields, crop areas or input use. Consistent with the narrower definitions of heat, most of the heat effects become larger in amplitude when using higher thresholds. The single variable that is not robust to alternative thresholds for measuring heat relates to barley yields; yet, the results are robust when measuring heat over the whole year (instead of the growing season only).

Time dimension. Our main estimations condition the weather variables on region fixed effects. Standard in the literature (Blanc and Schlenker, 2017), these location fixed effects allow purging for the potential confounding effects of unobserved but time-invariant regional characteristics that could be correlated with both agricultural outcomes and weather conditions (or land registry implementation). Authors in this literature however sometimes complement these location fixed effects with additional factors to control for the time dimension. Indeed, Greek regions face changing economic conditions (e.g., technological progress, changes in prices or policies, etc.), that may be correlated with our dependent and independent variables. These variables are typically common to all regions in Greece, such that these additional controls would only vary in their temporal dimension.

Table A3 shows the results of our sensitivity analyses when additionally complementing our preferred estimations with (i) international crop prices, (ii) quadratic time trend or (iii) year fixed effects. Most of the interaction terms remain statistically significant under these alternative specifications (at least, none significantly turn to the other sign). Our results on input use are particular robust to all of these changes. Those for crop yields and areas are somehow less robust, notably when including year fixed effects (where most estimates turn null statistically). As noted by Fisher et al. (2012), adding year fixed effects When working on a small area like Greece may however remove too much of useful variations for the identification – as largest temperature shocks mostly come from their temporal instead of their spatial dimension (i.e., yearly temperatures are largely correlated over space). This is typically what our imprecise estimates there would reflect.

Outcome variables. In the main regressions, our outcome variables regarding agricultural outcomes are log-transformed. Yet, some of observations include zeros for these dependent variables (at least regarding crop areas and agricultural inputs), implying that we had to add one to include these variables (see Tables 3 and 4 of the main text). Table A4 shows the results when using alternative transformation of the dependent variables, either using the inverse hyperbolic sine transformation (arcsinh) or the normalization by the mean of the control group (regional units without cadastral reform), as suggested by (Chen and Roth, 2024). Once again, our results regarding input use are particularly robust to these changes. Those on crop yields and areas are somehow less robust, even if all estimates conserve the same signs than those of our preferred estimates.

Spatial correlation. The main regressions correct for serial correlation by clustering standard errors at the regional unit level. Yet, the literature considers that, when working on temperature impacts, one may need to additionally correct for spatial correlation (given the high correlation of yearly temperature measurements over space; see Auffhammer et al., 2013, for example). To account for potential spatial correlations, we additionally correct the standard errors with the (Conley, 1999)'s approach, allowing spatial correlation ranging from 50 km to 500 km based on the centroids of each regional unit. Table A5 shows that all our main results remain statistically significant, whatever the threshold retained.

Timing of land registry. In our main specification, the variable $Registry_{i,t}$ informing on whether the region i has received the land registry in year t only takes the value 1 two years after the official start of the registry implementation (and 0 otherwise). Such a two-year delay is assumed to reflect the fact that it takes more than one year to complete the land registry, and then for the farmers to change their cropping practices. Such a delay was also implemented by Diao and Song (2024) when working on the impact of the Hellenic Cadaster program on the occurrence of wildfires in Greece.

To test whether our results are robust to changes in this definition, we re-perform our main analyses by replacing this two-year delay by a Z-year delay (Z$\in$ $[0;4]$ – that is, by shifting the timing of the land registry in our specification by X$\in$ $[-2;2]$. Figures A13 to A15 show the estimated interaction term when varying such a definition of $Registry_{i,t}$. Standing for falsification tests, these figures show that the timing of land registry matters and that our timing of land registry captures the reality. Indeed, all the interactions effects appear to be significantly non-null at the 90% statistical level after two years (as in our preferred analyses), and to persist through the fourth year.[A1] Conversely, the interaction terms are non-significantly non-null before, highlighting the time-consuming process of completing the land registry program for each region.

[A1]No results are obtained for labor when the timing of the cadastral reform is delayed, as the most recent labor data is from 2016, while the earliest cadastral reform occurred in 2014.

Table A2: Estimated interactions of heat with land registry with alternative heat measurements

	Wheat	**Barley**	**Maize**
	PANEL A. CROP YIELDS		
Benchmark	0.0018 ***	0.0015 *	0.0022 ***
	(0.0006)	(0.0008)	(0.0005)
Benchmark with KDD^{30} over the growing season	0.0031 ***	0.0020	0.0036 ***
	(0.0010)	(0.0015)	(0.0008)
Benchmark with KDD^{32} over the growing season	0.0063 ***	0.0034	0.0068 ***
	(0.0022)	(0.0033)	(0.0019)
Benchmark with KDD^{34} over the growing season	0.0166 ***	0.0073	0.0167 ***
	(0.0062)	(0.0103)	(0.0061)
Benchmark with KDD^{28} over the whole year	0.0016 ***	0.0014 *	0.0020 ***
	(0.0006)	(0.0008)	(0.0004)
	PANEL B. CROP AREAS		
Benchmark	-0.0024	-0.0024 *	-0.0035 **
	(0.0013)	(0.0012)	(0.0015)
Benchmark with KDD^{30} over the growing season	-0.0031	-0.0041 **	-0.0060 **
	(0.0019)	(0.0019)	(0.0023)
Benchmark with KDD^{32} over the growing season	-0.0050	-0.0059 *	-0.0102 **
	(0.0033)	(0.0034)	(0.0041)
Benchmark with KDD^{34} over the growing season	-0.0107 *	-0.0058	-0.0171 *
	(0.0055)	(0.0055)	(0.0089)
Benchmark with KDD^{28} over the whole year	-0.0022 *	-0.0023 *	-0.0033 **
	(0.0012)	(0.00012)	(0.0015)
	Machinery	**Labor**	**Irrigation**
	PANEL C. AGRICULTURAL INPUTS		
Benchmark	0.0026 **	0.0056 ***	0.0017 **
	(0.0010)	(0.0009)	(0.0008)
Benchmark with KDD^{30} over the growing season	0.0051 ***	0.0085 ***	0.0024 *
	(0.0018)	(0.0016)	(0.0124)
Benchmark with KDD^{32} over the growing season	0.0118 ***	0.0177 ***	0.0042 *
	(0.0028)	(0.0036)	(0.0026)
Benchmark with KDD^{34} over the growing season	0.0328 ***	0.0515 ***	0.0112
	(0.0823)	(0.0105)	(0.0068)
Benchmark with KDD^{28} over the whole year	0.0027 **	0.0057 ***	0.0018 **
	(0.0011)	(0.0008)	(0.0008)

NOTE. This table presents the estimates of the effects of killing degree days on regional (i) crop yields (Panel A), (ii) crop areas (Panel B) and (iii) agricultural inputs (Panel C), depending on whether the region has received the cadastral reform before the last two years. The column headlines refer to the crop or input considered. 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 interactions of heat with land registry with alternative specifications

	Wheat	**Barley**	**Maize**
	Panel A. Crop yields		
Benchmark	0.0018 ***	0.0015 *	0.0022 ***
	(0.0006)	(0.0008)	(0.0005)
Benchmark + future international prices	0.0020 ***	0.0016 **	0.0024 ***
	(0.0005)	(0.0008)	(0.0005)
Benchmark + quadratic time trend	0.0018 ***	0.0008	0.0011 *
	(0.0006)	(0.0008)	(0.0006)
Benchmark + year fixed effects	0.0010	0.0008	0.0021 ***
	(0.0007)	(0.0008)	(0.0006)
	Panel B. Crop areas		
Benchmark	-0.0024	-0.0024 *	-0.0035 **
	(0.0013)	(0.0012)	(0.0015)
Benchmark + future international prices	-0.0023	-0.0031 **	-0.0041 ***
	(0.0014)	(0.0014)	(0.014)
Benchmark + quadratic time trend	-0.0030 **	0.0004	-0.0013
	(0.0012)	(0.0016)	(0.0019)
Benchmark + year fixed effects	-0.0023	-0.0001	-0.0018
	(0.0014)	(0.0016)	(0.0019)
	Machinery	**Labor**	**Irrigation**
	Panel C. Agricultural Inputs		
Benchmark	0.0026 **	0.0056 ***	0.0017 **
	(0.0010)	(0.0009)	(0.0008)
Benchmark + future international prices	0.0027 ***	0.0059 ***	0.0016 *
	(0.0010)	(0.0009)	(0.0008)
Benchmark + quadratic time trend	0.0023 **	0.0059 ***	0.0027 ***
	(0.0010)	(0.0009)	(0.0008)
Benchmark + year fixed effects	0.0018 *	0.0059 ***	0.0029 **
	(0.0010)	(0.0009)	(0.0011)

Note. This table presents the estimates of the effects of killing degree days on regional (i) crop yields (Panel A), (ii) crop areas (Panel B) and (iii) agricultural inputs (Panel C), depending on whether the region has received the cadastral reform before the last two years. The column headlines refer to the crop or input considered. 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 A4: Estimated interactions of heat with land registry with alternative outcome transformations

	Wheat	Barley	Maize
	PANEL A. CROP YIELDS		
Benchmark	0.0018 ***	0.0015 *	0.0022 ***
	(0.0006)	(0.0008)	(0.0005)
arcsinh($y^k_{i,t}$)	0.0004 ***	0.0003	0.0015 ***
	(0.0001)	(0.0002)	(0.0003)
CR($y^k_{i,t}$)	0.0018 ***	0.0014	0.0023 ***
	(0.0007)	(0.0009)	(0.0007)
	PANEL B. CROP AREAS		
Benchmark	-0.0024	-0.0024 *	-0.0035 **
	(0.0013)	(0.0012)	(0.0015)
arcsinh($a^k_{i,t}$)	-0.0024 **	-0.0024 *	-0.0035 ***
	(0.0014)	(0.0012)	(0.0015)
CR($a^k_{i,t}$)	-0.0069 *	-0.0037	-0.0016
	(0.0040)	(0.0036)	(0.0025)
	Machinery	**Labor**	**Irrigation**
	PANEL C. AGRICULTURAL INPUTS		
Benchmark	0.0026 **	0.0056 ***	0.0017 **
	(0.0010)	(0.0009)	(0.0008)
arcsinh($x^k_{i,t}/A_{i,t}$)	0.00002 *	0.0052 ***	0.00002 *
	(0.00001)	(0.0009)	(0.00002)
CR($x^k_{i,t}/A_{i,t}$)	0.0009 *	0.0037 **	0.0014 ***
	(0.0005)	(0.0014)	(0.0015)

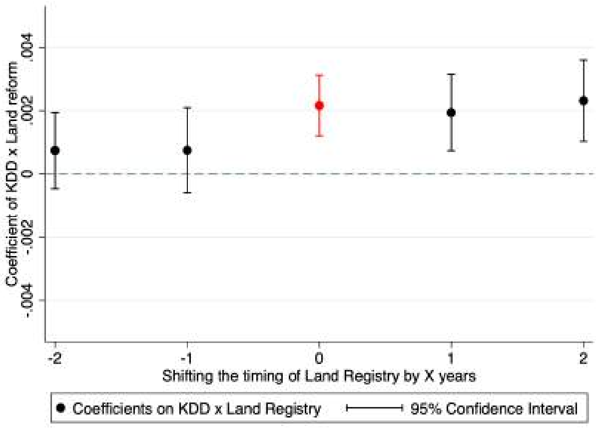
NOTE. This table presents the estimates of the effects of killing degree days on regional (i) crop yields (Panel A), (ii) crop areas (Panel B) and (iii) agricultural inputs (Panel C), depending on whether the region has received the cadastral reform before the last two years. The column headlines refer to the crop or input considered. 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 A5: Estimated interactions of heat with land registry with Conley (1999)'s correction

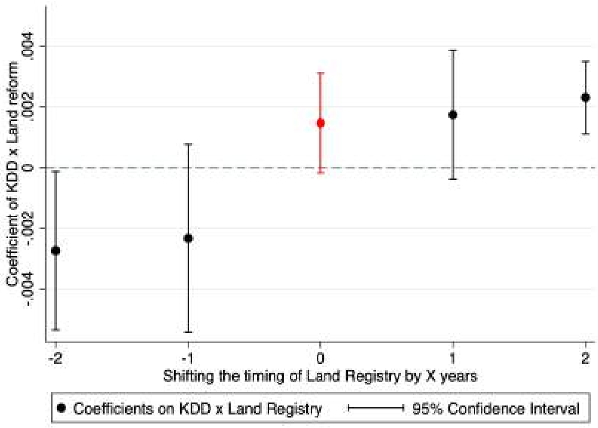
	Wheat	**Barley**	**Maize**
	Panel A. Crop yields		
Benchmark	0.0018 ***	0.0015 *	0.0022 ***
	(0.0006)	(0.0008)	(0.0005)
Benchmark + spatial correlation within 50 km	0.0018 ***	0.0015 *	0.0022 ***
	(0.0006)	(0.0008)	(0.0005)
Benchmark + spatial correlation within 100 km	0.0018 ***	0.0015 *	0.0022 ***
	(0.0006)	(0.0009)	(0.0005)
Benchmark + spatial correlation within 200 km	0.0018 ***	0.0015 *	0.0022 ***
	(0.0005)	(0.0008)	(0.0004)
Benchmark + spatial correlation within 500 km	0.0018 ***	0.0015 *	0.0022 ***
	(0.0003)	(0.0005)	(0.0003)
	Panel B. Crop areas		
Benchmark	-0.0024 *	-0.0024 **	-0.0035 **
	(0.0013)	(0.0012)	(0.0015)
Benchmark + spatial correlation within 50 km	-0.0024 *	-0.0024 **	-0.0035 ***
	(0.0013)	(0.0012)	(0.0014)
Benchmark + spatial correlation within 100 km	-0.0024 **	-0.0024 *	-0.0035 ***
	(0.0011)	(0.0013)	(0.0011)
Benchmark + spatial correlation within 200 km	-0.0024 *	-0.0024 *	-0.0035 ***
	(0.0013)	(0.0013)	(0.0009)
Benchmark + spatial correlation within 500 km	-0.0024 **	-0.0024 **	-0.0035 ***
	(0.0010)	(0.0012)	(0.0006)
	Machinery	**Labor**	**Irrigation**
	Panel C. Agricultural Inputs		
Benchmark	0.0026 **	0.0056 ***	0.0017 **
	(0.0010)	(0.0009)	(0.0008)
Benchmark + spatial correlation within 50 km	0.0026 **	0.0056 ***	0.0017 **
	(0.0012)	(0.0009)	(0.0009)
Benchmark + spatial correlation within 100 km	0.0026 **	0.0056 ***	0.0017 **
	(0.0012)	(0.0008)	(0.0010)
Benchmark + spatial correlation within 200 km	0.0026 **	0.0056 ***	0.0017 **
	(0.0012)	(0.0008)	(0.0011)
Benchmark + spatial correlation within 500 km	0.0026 **	0.0056 ***	0.0017 **
	(0.0009)	(0.0008)	(0.0009)

Note. This table presents the estimates of the effects of killing degree days on regional (i) crop yields (Panel A), (ii) crop areas (Panel B) and (iii) agricultural inputs (Panel C), depending on whether the region has received the cadastral reform before the last two years. The column headlines refer to the crop or input considered. 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.

a) Wheat Yield



b) Barley Yield



c) Maize Yield

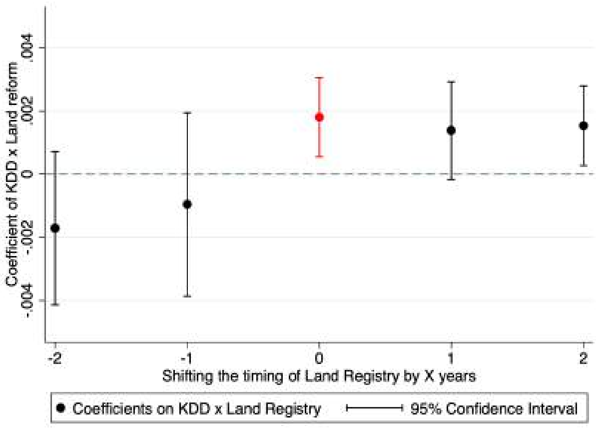
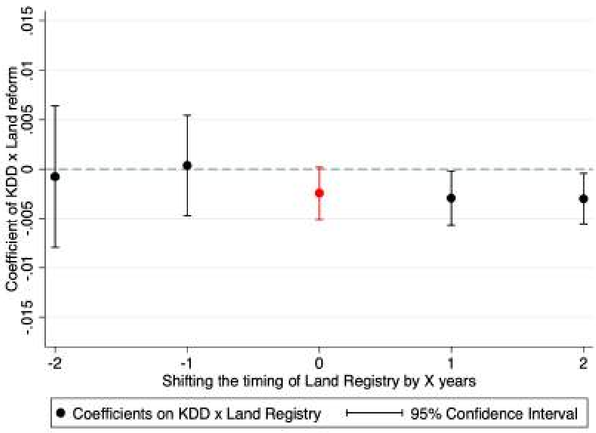


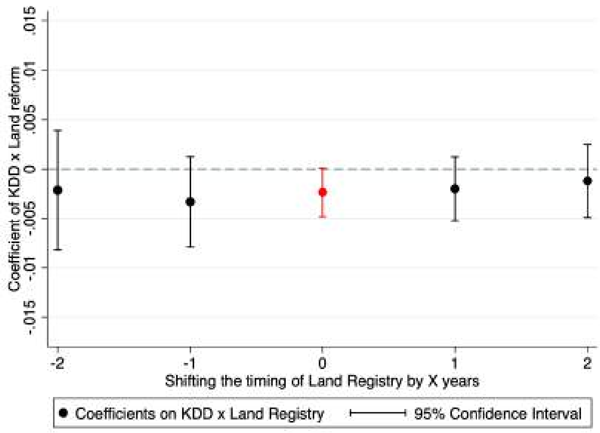
Figure A13: Results with the timing of land registry delayed by X years

NOTE. The figure shows the coefficient of KDD^{28} × Registry reform in Table 2 by delaying the timing of Land Registry by X years. Markers represent point estimates and error bars represent 95% confidence intervals constructed based on standard errors clustered at the regional unit level to account for serial autocorrelation. The red estimates reflect those used in our preferred analyses, where we assume that the effects of land registry on cropping practices start two years after the initiation of the reform in the region.

a) Wheat Area



b) Barley Area



c) Maize Area

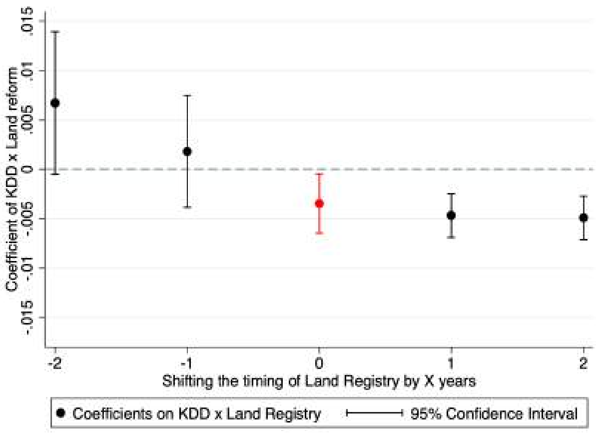
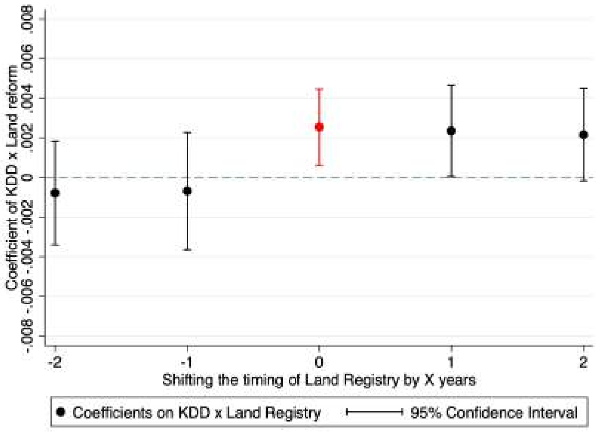


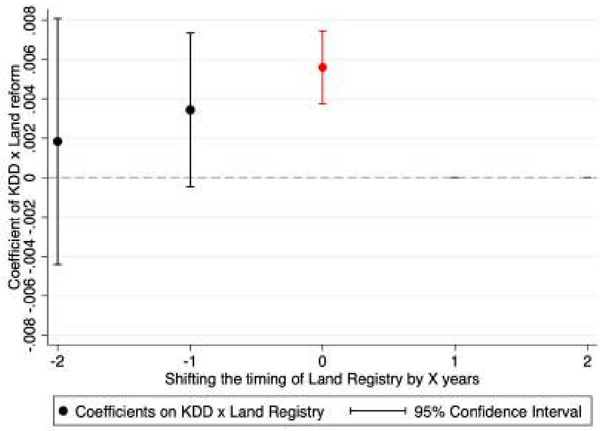
Figure A14: Results with the timing of land registry delayed by X years

NOTE. The figure shows the coefficient of KDD^{28} $\times$ Registry reform in Table 3 by delaying the timing of Land Registry by X years. Markers represent point estimates and error bars represent 95% confidence intervals constructed based on standard errors clustered at the regional unit level to account for serial autocorrelation. The red estimates reflect those used in our preferred analyses, where we assume that the effects of land registry on cropping practices start two years after the initiation of the reform in the region.

a) Machinery



b) Labor



c) Irrigation

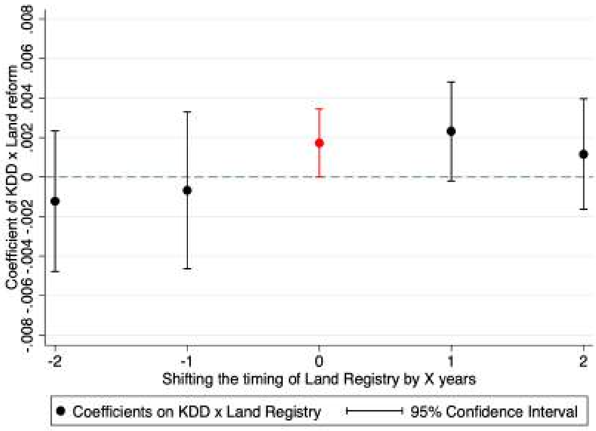


Figure A15: Results with the timing of land registry delayed by X years

NOTE. The figure shows the coefficient of KDD^{28} × Registry reform in Table 4 by delaying the timing of Land Registry by X years. Markers represent point estimates and error bars represent 95% confidence intervals constructed based on standard errors clustered at the regional unit level to account for serial autocorrelation. The red estimates reflect those used in our preferred analyses, where we assume that the effects of land registry on cropping practices start two years after the initiation of the reform in the region.

A5 Ruling out alternative mechanisms

This appendix displays the results of the estimations regarding our analyses on potential alternative mechanisms explaining the differing effects of heat on crop yields and practices depending on whether the Greek region has received the land registry reform or not. Table A6 shows the results for other areas. Table A7 shows the results for burnt areas. Table A8 shows the results for animal density. As discussed in the main text (see Section 6.5), all the results from these tables suggest no differing impacts for heat on these outcomes depending on the quality of land property rights – as testified by the fact that the interaction estimate between heat and the registry reform is never statistically significant in Tables A6 to A8.

Table A6: Estimated impacts of heat on other areas according to the presence of land registry

	Dependent variable: $log(1 + a^k_{i,t})$		
	Total farmland	**Permanent crops**	**Fallows**
KDD^{28}	0.0017 ***	0.0005	0.0035 *
	(0.0004)	(0.0003)	(0.0010)
KDD^{28} × Registry reform	0.0009	-0.0034	0.0022
	(0.0015)	(0.0022)	(0.0034)
Registry reform	-0.0256	0.3146 *	0.2457
	(0.1134)	(0.1611)	(0.2670)
Precipitation controls	Yes	Yes	Yes
Region fixed effects	Yes	Yes	Yes
χ^2 joint Student test for KDD^{28}	2.7469 *	1.6218	3.0195 *
χ^2 joint Wald test for registry	0.0676	5.3857 **	5.9542 **
Adj. R^2	0.9767	0.9864	0.7862
Observations	513	513	513

NOTE. This table presents the estimates of the effects of killing degree days on regional areas, depending on whether the region has received the cadastral reform before the last two years. The column headlines refer to area considered. Killing degree days are measured as the cumulative days spent above 28°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.

Table A7: Estimated impacts of heat on burnt areas according to the presence of land registry

	Dependent variable: $log(1+a_{i,t}^k)$		
	Burnt agricultural areas	**Burnt forest areas**	**Burnt urban areas**
KDD^{28}	0.0057	0.0057 *	0.0008
	(0.0052)	(0.0029)	(0.0023)
KDD^{28} × Registry reform	0.0041	-0.0049	0.0047
	(0.0151)	(0.0051)	(0.0054)
Registry reform	-2.5160 *	0.4377	-0.7438
	(1.5302)	(0.4185)	(0.5887)
Precipitation controls	Yes	Yes	Yes
Region fixed effects	Yes	Yes	Yes
χ^2 joint Student test for KDD^{28}	0.4288	0.0310	1.0398
χ^2 joint Wald test for registry	6.2241 ***	1.1219	3.3068 *
Adj. R^2	0.3994	0.2552	0.2930
Observations	513	513	513

NOTE. This table presents the estimates of the effects of killing degree days on regional 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 28°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 A8: Estimated impacts of heat on animal density according to the presence of land registry

	Dependent variable: $log((1+z_{i,t}^k)/A_{i,t})$			
	Pigs	**Sheeps**	**Goats**	**Cows**
KDD^{28}	0.0015	-0.0010	0.0003	-0.0004
	(0.0011)	(0.0012)	(0.0004)	(0.0008)
KDD^{28} × Registry reform	-0.0025	0.0050	-0.0001	-0.0056
	(0.0036)	(0.0040)	(0.0007)	(0.0034)
Registry reform	0.684	-0.4364	-0.0595	0.8248
	(0.5299)	(0.3310)	(0.0908)	(0.5717)
Precipitation controls	Yes	Yes	Yes	Yes
Region fixed effects	Yes	Yes	Yes	Yes
χ^2 joint Student test for KDD^{28}	0.1238	1.0639	0.1133	4.5072 *
χ^2 joint Wald test for registry	0.7580	1.5507	0.3225	1.7066
Adj. R^2	0.7206	0.7201	0.9317	0.8658
Observations	511	511	511	511

NOTE. This table presents the estimates of the effects of killing degree days on the density of animals in head per hectare per hectare of the whole regional agricultural area (minus fallows), depending on whether the region has received the cadastral reform before the last two years. The column headlines refer to animal considered. Killing degree days are measured as the cumulative days spent above 28°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.