Assessing the Impact of Drought on Dairy Farming in Italy: Economic, Land Use, and Resource Management under Climate Change

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Abstract

This study assesses the impact of drought on Italian dairy farms and its interplay with market shocks, while identifying short-run coping strategies. An agro-supply economic model is applied to a FADN sample of 930 dairy farms. Farm-level responses are analyzed in terms of land use, economic outcomes, and resource use linked to increased irrigation water requirements and crop pattern adjustments. Climate data are employed to estimate irrigation water requirements and simulate drought scenarios, while feed prices increase to capture market shocks. Results show that farms are able to maintain incomes and herd size under drought if market conditions remain stable and feed purchases remain accessible. However, when market pressure intervenes, dairy farms reduce herd size and shift towards on-farm feed production, increasing water and production intensity. This strategy led to environmental, social, and economic consequences such as contracting costs, reducing employment, and cutting herd sizes with significant income losses. Direct impacts of drought on animals and milk productivity, which are not explicitly modelled, may further amplify the overall sectoral effects. The assessment of farm vulnerability under combined climate and market shocks provides insights that can inform future policy and research considerations.

Keywords: Droughts, Mathematical Programming, FADN, Dairy Farms, Market Reliance

JEL Codes: C61; Q12; Q15; Q18; Q54

1. Introduction

Drought is one of the main threats impacting the agricultural sector, pushing farmers to pursue strategies to adapt to adverse climate conditions. Recent studies, such as Beillouin et al. (2020), highlighted the negative impact of drought on European crop yields, with losses tripled between 1964 and 2015 (Brás et al., 2021), while others, such as Tramblay et al. (2020), affirm that the Mediterranean is the most exposed region to this threat. In the near future, the frequency and intensity of these events are expected to worsen, with a negative impact both on crop yields and water availability (Wada et al., 2010). Therefore, agriculture in the Mediterranean is called to cope with increasing drought risks while maintaining production and income levels (García-León et al., 2021). Specifically, dairy farms are among the most affected by drought and heat waves, with climate pressure impacting all stages of the production value chain (Gauly and Ammer, 2020; Godde et al., 2021).

Effects of climate change on dairy cattle can be grouped as direct impacts on animals, i.e., heat and water stress, or indirect impacts such as modification in the geographical distribution of vector-borne diseases, quality, and quantity of feed and water (Rivera-Ferre et al., 2016; Rojas-Downing et al., 2017). Among these indirect impacts, feed availability and quality are particularly critical. The main feed crops, such as soybean and maize, are among the most affected by high temperatures and water scarcity (Lionello and Scarascia, 2018; Maitah et al., 2021; Osborne et al., 2013; Soares et al., 2022). This trend is likely to cause land use changes, as farmers will undertake adaptation strategies to mitigate drought impacts and maintain productivity. Moreover, reduced internal production and lower national supply may increase farms' exposure to feed price volatility (Solazzo et al., 2023). This complex context highlights that increasing feed prices represent an additional source of pressure, interacting with climate stress and further shaping farmers' adaptation strategies.

The dairy sector is one of the key pillars of the agri-food production in Italy, generating more than 5.47 billion euros in exports in 2023 (ISMEA, 2024). Moreover, it is linked to several high-value supply chains, i.e., Protected Designation of Origin (PDO) cheeses, such as Grana Padano and Parmigiano Reggiano. For these reasons, analyzing the impact of drought and market stress on its economic and productive outcomes is critical. This study's objective is to analyze Italian dairy farms' adaptation strategies to drought-induced changes in crop production and irrigation requirements and their interaction with market volatility. Adaptation strategies are defined here as short to medium-term adjustments in production choices and input allocation, such as changes in crop allocation, resource use, and management practices. While adaptation strategies can also refer to long-term transformations, i.e., technological innovation, investments, or farm reorganization, the modelling framework adopted in this work focuses on short-run coping strategies, hence providing a snapshot of the impact of drought on the current structure of the Italian dairy sector.

In this framework, drought impacts are represented through changes in crop irrigation water requirements, which affect land allocation, on-farm feed and forage production, and dependence on market purchases, excluding direct impacts on animals. By isolating this mechanism, the analysis captures how climate-induced changes in crop systems translate into economic responses at the farm level. Therefore, the results should be interpreted as representing indirect patterns through which drought affects livestock rather than the full spectrum of responses of dairy production systems to drought. The methodological contribution of the paper lies in linking microeconomic farm data with detailed territorial climate information to estimate irrigation water requirements and inform the AGRITALIM model. The specific objectives are (i) to evaluate the impact of drought on economic performance, land use, and resource allocation at the farm level and (ii) to assess the combined influence of increasing feed prices and severe drought on farm economic results and land use choices.

The analysis employs a Farm Accountancy Data Network (FADN) sample of 930 specialized dairy cattle farms for the year 2021. The simulations include two climate scenarios of increasing drought intensity and three scenarios of increasing feed prices. Drought conditions are simulated by estimating crop-specific irrigation needs as the difference between evapotranspiration (ET) and precipitation (P). This allows the model to reflect how climate heterogeneity impacts irrigation demand. This methodology integrates climate data with economic modeling, offering a robust framework able to evaluate the dairy sector's ability to cope with drought while managing market pressure.

2. Data and research methodology

2.1. The AGRITALIM model

To reach the stated objectives, the analysis employs an agro-supply economic model, i.e., AGRITALIM (Cortignani et al., 2022), operating at the farm level and leveraging detailed microeconomic data from the Italian Farm Accountancy Data Network (FADN) database. It is calibrated through the Positive Mathematical Programming (PMP) approach (Howitt, 1995; Paris and Arfini, 1995) and maximizes the farm operating income, while taking into account inputs and output prices, yields, Common Agricultural Policy (CAP) subsidies, and depreciation costs to account for capital invested on the farm. Further details, including the general mathematical formulation of the model, are provided in the Appendix.

Like all economic models based on MP, certain methodological limitations need to be acknowledged to better contextualize the results. A first limitation intrinsic in the PMP calibration approach emerges when introducing explicit technologies and management practices. In the absence of detailed data on their current adoption, model calibration becomes challenging, and zero adoption is assumed in the baseline. More specifically, AGRITALIM does not explicitly incorporate substitution elasticities among production activities, which could be derived from partial equilibrium models such as CAPRI. This limitation is partially mitigated by the articulated structure of model constraints, which explicitly represents the main resources involved in crop and livestock production, i.e., land, water, labor, and feed, and allows the model to approximate equilibrium conditions in factor markets.

AGRITALIM is calibrated based on current agronomic techniques, crop rotations, and technologies, providing a static representation of farmer responses in the short to medium term. Long-term structural adjustments, such as technological adoption or farm reorganization, are not explicitly captured. The model assumes rational farm behavior aimed at maximizing operating income and does not account for behavioral aspects such as risk aversion or decision-making under uncertainty. Furthermore, production uncertainty is not explicitly represented, as the model does not consider yield variability, crop quality deterioration, pest outbreaks, fungal attacks, or mycotoxin risks.

Despite these limitations, AGRITALIM's main strength lies in its ability to represent the entire sample of the Italian FADN database, capturing the structural, geographic, and productive heterogeneity of Italian farms. Furthermore, by explicitly modelling variations in key production resources, the framework allows the simulation of climate-related shocks (Buttinelli et al., 2026), policy interventions (Dell'Unto and Cortignani, 2025), and market dynamics.

In this work, the AGRITALIM model is informed by a FADN sample of 930 specialized dairy farms for the year 2021[1]. Descriptive statistics for the sample are shown in Table 1. Concerning the sample distribution, 27.2% of the farms are located in the North-West, 40.2% in the North-East, 6.6% in the Centre, and 26.0% in the South. As for altitude, about half of the farms are located in the Mountains (51.7%), while 25.4% and 22.9% are located in the Plains and the Hills, respectively. Finally, small farms (<15 ha) represent 28.1%, medium farms (15-40 ha) 36.5%, and big farms (>40 ha) 35.4%.

Table 1: Descriptive Statistics for the selected FADN sample (Mean, Standard Deviation, Minimum, and Maximum)

Variable	UM	Mean	Std. Dev.	Min	Max
Operating Income	€	90,881	192,396	-86,801	2,555,214
Work	Hours	3,328	2,778	0.0	26,000
Hired Work	Hours	513	1,627	0.0	22,194
Family Work	Hours	2,816	1,902	0.0	13,200
Water	m^3	24,155	97,698	0.0	1,639,417
Groundwater	m^3	2,737	22,493	0.0	489,721
Land	Hectares	50	69	0.0	509
Irrigated Land	*Hectares*	*8*	*27*	*0.0*	*336*
LSU	Livestock Units	108	160	0.9	1,441
Feed	Kg	2,980	5,773	0.0	55,881

2.2. Drought Scenarios and Irrigation Water Requirements

Simulated drought scenarios are based on crop irrigation water requirements changes caused by climatic pressures and are therefore linked to land and water allocation. Direct animal-level impacts of drought are not explicitly modelled, as AGRITALIM represents crop–livestock interactions through resource

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[1] Specifically, TF 45 has been selected as it refers to "Specialized Dairy Cattle Farms".

allocation mechanisms rather than impacts on animals and their productive performance. Scenarios are built on a 40-year climatological analysis, useful to identify severe drought events in Italy. Daily precipitation (P) and Standard Evapotranspiration (ET_0) were derived from data from the ERA5-Land dataset (Muñoz Sabater, 2019), produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) and provided through the Copernicus Climate Change Service (C3S) through the Penman-Monteith methodology (Allen, 1999; Singer et al., 2021). To capture water balance anomalies relevant to crop phenology and irrigation needs, P and ET_0 were aggregated over two growing periods (April–September for summer, October–March for winter) and at the scale of agricultural regions (Quaresima et al., 2024)[2]. Water stress climatology was assessed using the Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010), which quantifies deviations from long-term $P - ET_0$ balance at the agricultural region level for these six-month periods (SPEI6). SPEI6 is chosen to identify drought events over the 40-year period considered and to classify them using the following thresholds: moderate drought (SPEI6 ≥ -1), severe drought ($-1 >$ SPEI6 ≥ -1.5), and extreme drought (SPEI6 ≤ -2) (McKee et al., 1993).

The summers of 2017 and 2003 were particularly critical and were identified as the foundation for our drought scenarios. The rationale is forward-looking: given the increasing frequency and intensity of droughts, it is plausible that events like those of 2003 and 2017 may become more frequent or even represent the “new normal”. The assumption is that recent drought events are likely to recur in the present and that farmers are expected to anticipate these climate challenges and plan their production choices accordingly (Iglesias et al., 2016).

Two drought scenarios were then simulated: D^{+}, based on 2017 climate conditions when drought affected 30% of regions, and D^{++}, simulating 2003 conditions with drought impacting 60% of regions, especially in Northern and Central Italy. The baseline scenario, instead, is characterized by 15% of agricultural

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[2] According to the Italian National Institute of Statistics (ISTAT) definition, an agricultural region consists of groups of municipalities based on rules of territorial continuity, homogeneous in relation to certain natural and agricultural characteristics, and subsequently aggregated by altitude zone.

regions affected by severe drought, allowing for the simulation of progressively increasing levels of drought intensity. Overall, the three scenarios represent progressively increasing drought intensity and spatial extent, with 15%, 30%, and 60% of agricultural regions affected by severe drought. The spatial distribution of drought is shown in Figure 1, as spatial heterogeneity in farm-level results is an intentional feature of the model, reflecting differences in local drought impact and farm characteristics.

The choice of 2021 as a baseline was hence driven first of all by climate conditions, but also by economic, production, and policy considerations. It ensures relevance to current market conditions, production techniques, and farm structures. Furthermore, it is the most recent year available in the FADN database, not heavily affected by external geopolitical shocks such as the pandemic and the Ukrainian conflict, or the introduction of a new CAP programming period.

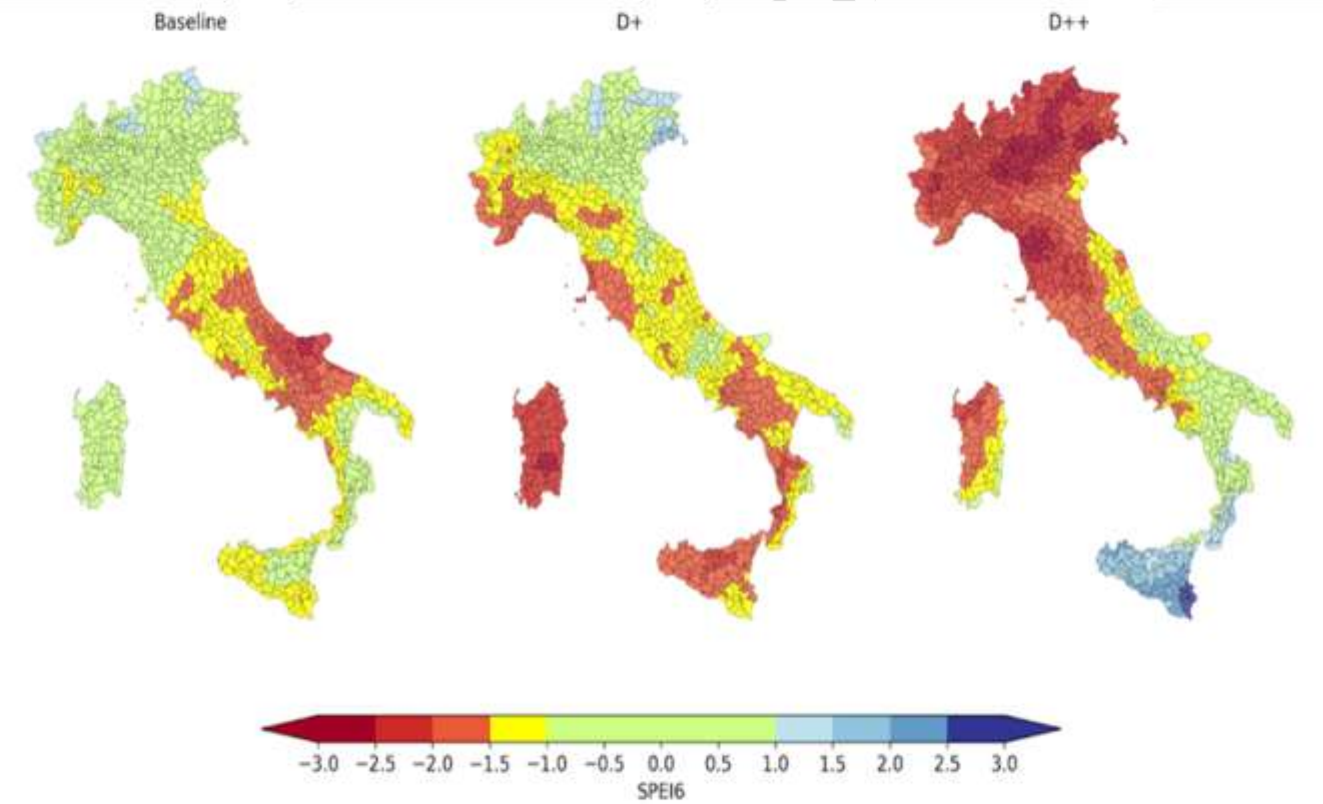

Figure 1. Spatial distribution of September scenario, presenting the cumulative P and ET_0 from April to September, for the three scenarios: baseline, D^{+}, and D^{++}.

To link the climate scenario with the AGRITALIM model, specific crop irrigation requirements were used as the key input. Indeed, the relationship between irrigation water use and availability at the farm level is one of the main constraints embedded in the AGRITALIM model, and this characteristic allows it to capture how changes in irrigation water demand could influence agricultural production, resource allocation, and consequently land use and economic outcomes. This approach allows for the identification of farmers' adaptation strategies to increased water requirements driven by drought conditions. Specifically, AGRITALIM considers, for each crop and farm, both the irrigation volumes and the irrigation water source, allowing for adjustments in irrigation water requirements, determining changes in land use and economic results. Irrigation requirements are recalculated according to the specific climatic conditions observed in each agricultural region, so that drought shocks are spatially differentiated across farms depending on their geographical location. Heterogeneous farm-level results emerge from the interaction between territorial climate shocks and farm structural and economic characteristics, rather than from the spatial allocation of drought conditions alone.

Reflecting farmers' rational behavior, the main underlying assumption is that farmers are fully aware of the climatic conditions and adapt by optimizing land use and input allocations in response to drought. Therefore, irrigation needs are explicitly integrated into the agro-supply model as key input requirements and re-estimated for each scenario considered (i.e., the baseline, D^{+} , and D^{++}). The methodological approach is in accordance with the FAO Guidelines for Computing Crop Water Requirements (FAO, 1998) and Italian Ministerial Decree July 31 2015, as shown in Equation 1:

$$W = 10\,\frac{|ET_p - P_n|}{e_{ap} e_d e_a} A \Delta t \tag{1}$$

Where the irrigation requirements (W) for an area A (ha) over a period Δt (in days)[3] are estimated based on net rainfall P_n, (> 5 and < 50 mm) and crop evapotranspiration (ET_p) at the agricultural region level. ET_p is obtained by multiplying ET_0 by specific crop coefficients (k_c). The multiplier 10 converts requirements in m^3, being ET_p and P_n expressed in mm/day. Additionally, efficiency coefficients are:

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[3] The Δt considered covers the spring-summer season (April 1st–September 30th), fall-winter (October 1st–March 31st), and a specific period for winter vegetables (July 1st–December 30th).

e_{ap} which pertains to field application, e_d for distribution and e_a for the supply system. Weighted averages for e_{ap} were calculated using FADN information and soil texture coefficients. e_d was omitted for accuracy concerns, assuming consistent irrigation methods within crops across the same region. Instead, due to the lack of data on water distribution infrastructure (i.e., Water Users Associations), e_a was excluded. The choice of excluding these factors ensures consistency and comparability of the results, even though it potentially underestimates requirements for farms relying on less efficient irrigation systems and overestimates them for farms using more advanced water-saving technologies compared to others in the same region.

2.3. Price Scenarios

Market prices are one of the AGRITALIM model's key inputs. They influence production choices, resources, and land allocation, and the economic performance of each farm. Therefore, simulating variations in feed market prices allows the model to replicate and assess how market conditions interact with drought stress and how farms cope with these stresses. Empirical data support the simulation of progressive price increases.

Indeed, under drought stress, the consequences on feed and forage prices can be severe (Schaub and Finger, 2020). In 2003, drought hit Europe and North America, causing a reduction in cereal production and a lower productivity of up to 36% in Italy for maize (Ciais et al., 2005). In this scenario, feed prices rose by 13-16% (ISMEA, 2005). In 2012, similarly, drought affected the United States, Brazil, Argentina, and Italy, with lower maize and soybean global production (Rippey, 2015), with severe effects on the European livestock sector. Recently, in 2022, drought caused production losses in Italy, estimated for maize up to 23%. However, other exogenous shocks can influence the supply of feed and cereals. Indeed, in the same year, the simultaneous effect resulting from drought and the Russia-Ukraine conflict (Jagtap et al., 2022), as well as higher production costs driven by rising energy prices (Benoit and Mottet, 2023), caused direct impacts on feed prices by 25% (CREA, 2024). In addition, future trade policies, such as tariffs or import restrictions for feed crops such as soybeans from the US, could further affect feed prices. These shortcomings could be further exacerbated under drought stress, creating a vicious cycle of increasing demand from the national sector and reduced access to feed from the market due to scarce production or geopolitical tensions and trade policies.

The AGRITALIM model is able to simulate very small variations in input prices; hence, a series of incremental simulations was performed. However, for clarity and relevance, only the scenarios showing significant impacts are reported: +15%, +25%, and +50% (FP15, FP25, and FP50, respectively). These price increases are simulated exclusively under the most pressuring drought conditions, i.e., D^{++}, in order to capture worst-case outcomes and focus on the scenarios with the most critical implications. The increase in feed prices refers to the unit prices of purchased feed at the farm level. A uniform percentage increase was applied to all feed items relative to the baseline. This provides a methodological approach capable of focusing on the overall economic impact of rising feed costs, since the prices of feed components often vary in a correlated way, responding similarly to similar market and geopolitical pressures. Finally, the main objective of this price exercise is to assess how increases in feed costs interact with extreme drought conditions to influence farm income, land use, and resource allocation.

3. Results

The results for each scenario were obtained at the farm level. However, to provide measures of uncertainty, a bootstrap procedure was applied to the variations. This approach allows us to estimate robust average effects and obtain confidence intervals, reflecting the variability across the sample without relying on parametric assumptions (Ferrier and Hirschberg, 1997; Davison and Hinkley, 1997; Efron and Tibshirani, 1994).

The results are presented for the drought scenarios (D^{+} and D^{++}) alone, and for the combined effects of severe drought (D^{++}) and feed price increases (FP15, FP25, FP50), highlighting their impacts on economic outcomes (operating income), resource use (work, water, land, livestock units, feed), and land use changes for the main crops and crop groups.

3.1. Drought Impacts

Drought affects the specialized dairy farms under analysis mainly by altering land use and increasing the reliance on purchased feed. Under the D^{+} and D^{++}scenarios, farm income decreases by 0.3% and 1.4% respectively (Table 2), while Livestock Units (LSU) remain largely stable, with a slight reduction of 0.2% under D^{++}. This suggests that farms prioritize maintaining herd size to stabilize income. Feed purchase costs increase by 2.8% and 6.3% in the D^{+} and D^{++}scenario, respectively. Land and irrigated Land decrease by 1.3% and 3.4% in the D^{+} scenario, and by 4.2% and 6.7% in the D^{++} scenario. Finally, work reduces by 0.5% in the D^{+} scenario and by 1.9% in the D^{++} scenario. Irrigation water use decreases by 2.4% in the D^{+} scenario while it slightly increases by 1.1% in the D^{++} scenario, reflecting land use adjustments (Table 3). Groundwater, on the other hand, increases slightly under both scenarios, i.e. by 0.4% and 0.5%.

Indeed, the adaptation strategies undertaken by farms in response to drought and increased crop irrigation water requirements mainly consist of allocating irrigation water more efficiently while maintaining herd size and balancing the loss of on-farm production with feed purchases. Therefore, areas under hay crops decline by 0.6% and 2.0% in the D^{+} and D^{++} scenarios, respectively, with alfalfa decreasing by 3.2% and 5.4%, while ryegrass increases by 3.5% and 9.4%. Other hay crops remain stable in D^{+} and decline by 2.4% in D^{++}.

Silage crops show larger reductions (2.6 in D^{+} and 11.4 in D^{++}) and especially silage maize, which reduces by 4.5% in D^{+} and 18.4% in D^{++}. Instead, other silage crops such as barley and triticale increase by 1.0% in D^{+} and by 5.7% in D^{++}. However, this increase is not able to fully compensate for the Silage Maize area reduction, as confirmed by the increase in feed purchases.

Finally, grain crops reduced by 1.8% in D^{+} and 11.2% in D^{++}, mainly driven by grain maize. Pasture areas remain mostly stable, with slight increases of 0.1% and 0.4% under D^{+} and D^{++}, respectively. The mentioned results refer to average impacts across the sample. However, the confidence intervals reported in Tables 2 and 3 provide an indication of the variability across farms, showing that impacts can be stronger or milder than the average values reported.

3.2. Drought and Feed Price Dynamics

When severe drought (D^{++}) is combined with shocks on the feed market, the pressure on dairy farms increases. From the economic point of view (Table 4), this additional pressure has severe consequences on operating income, which decreases by 10.8%, 16.3%, and 24.8% under FP15, FP25, and FP50, respectively. At the same time, under these circumstances, LSU reduces sharply by 14.8% 20.9% and 32.4%. At the same time, feed purchases decrease by 29.5%, 42.0%, and 62.7%, respectively, under the three scenarios. However, percentage losses in operating income are less than proportional to the reduction of production activities and denote an increase in the efficiency of production processes, allowed by the cut in less productive (and less profitable) rearing activities.

On the other hand, land remains stable under the FP15 and FP25 while increasing by 2.3% under the FP50 scenario in order to offset the reduced purchases from the market with on-farm production. Similarly, irrigated land is reduced by 6.4% under the FP15 scenario, while slightly less (6.2% and 5.9%) under FP25 and FP50, respectively. In this case, water increases constantly under all the scenarios, by 1.7%, 2.0% and 2.3%, with groundwater increasing up to 1.3% under the most pressuring scenario (FP50). Finally, work reduces sharply, with reductions of 11.0% under FP15, 14.7% under FP25, and 21.8% under the FP50 scenario.

These adjustments in terms of resource use, especially water and land, are explained by the land use change shown in Table 5. Hay crop area increases by 5.4%, 8.4%, and 13.8% in the three simulated price scenarios. Specifically, alfalfa increases by 4.3%, 9.9%, and 22.0% respectively, while ryegrass increases sharply by 41.6%, 56.0% and 86.2%. This is due to the combination of producing feed on farm while replacing crops with less water-intensive alternatives. Silage crops, instead, although water-intensive, show a milder reduction across these scenarios (i.e., while the feed price increases, the area under silage crops tends to reduce less). Under FP15, these crops are reduced by 6.3%, and under FP25 by 11.2%, while under FP50, they remain stable. Silage maize reduces more, but following the same trend: by 14.0%, 11.2%, and 9.2%, respectively. Instead, other silage crops increase by 13.5%, 12.8%, and 14.9% under the three simulated scenarios.

Instead, grain crops decrease sharply, up to 18.4% in the FP50 scenario. To increase farm feed production, finally, pastures are reduced by 8.5% under FP15, 14.6% under FP25, and -20.3% under the FP50 scenario.

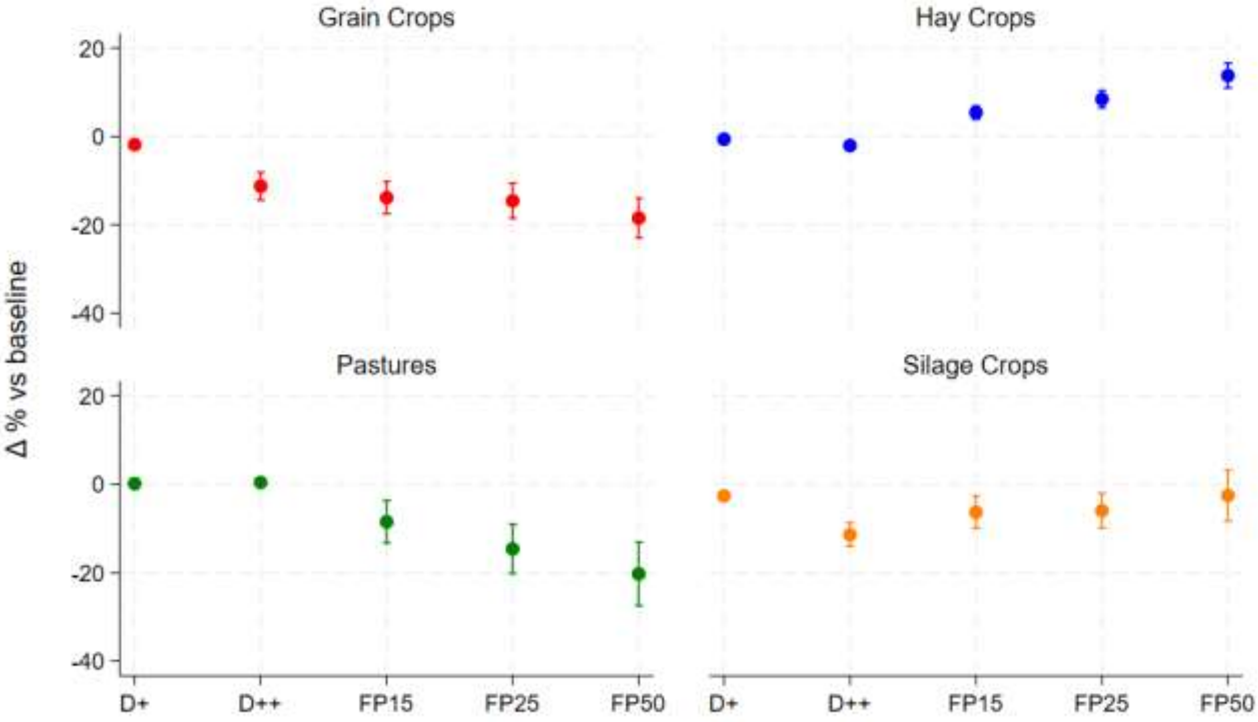

Figure 1: Percentage change in land use by crop group under the five simulated scenarios.

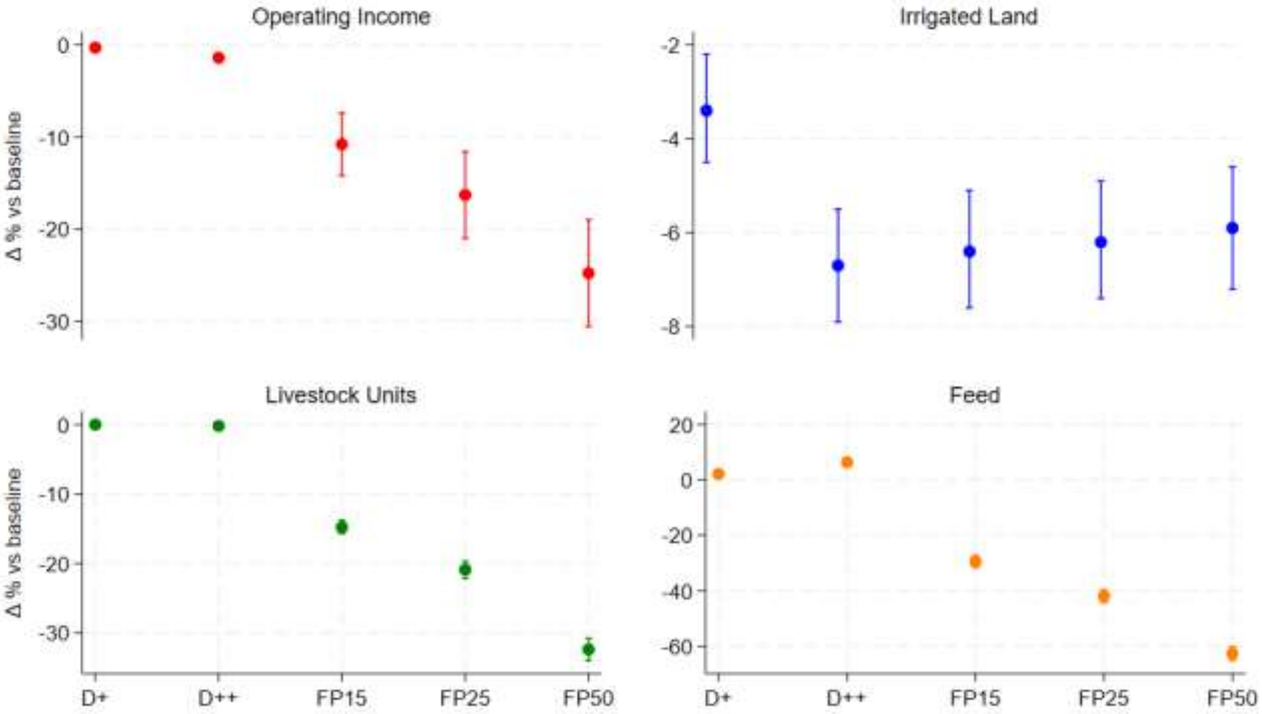

Figure 2: Percentage change vs. the baseline in economic, resource use and productive indicators under the five simulated scenarios .

Table 2: Impacts on economic outcomes and resource use under the D^{+} and D^{++} scenarios. Results are expressed as average percentage variations over the baseline.

	UM	Baseline	D^{+}			D^{++}		
Operating Income	M€	84.5	-0.3	***	[-0.4 ; -0.2]	-1.4	***	[-1.7 ; -1.1]
Work	M Hours	3.1	-0.5	***	[-0.6 ; -0.4]	-1.9	***	[-2.4 ; -1.5]
Water	M m3	22.5	-2.4	***	[-3.5 ; -1.3]	1.1	***	[0.8 ; 1.4]
Groundwater	M m3	*2.6*	*0.4*	***	[0.2 ; 0.5]	*0.5*	***	[0.3 ; 0.7]
Land	1000 hectares	46.8	-1.3	***	[-1.7 ; -1.0]	-4.2	***	[-5.1 ; -3.2]
Irrigated Land	1000 hectares	7.2	-3.4	***	[-4.5 ; -2.2]	-6.7	***	[-7.9 ; -5.5]
Nitrogen	M kg	0.8	-0.8	***	[-1.1 ; -0.5]	-4.0	***	[-4.9 ; -3.1]
LSU	1000 Livestock Units	101.0	0.0		[0.0 ; 0.0]	-0.2	**	[-0.3 ; -0.0]
Feed	M€	2.8	2.1	***	[1.4 ; 2.7]	6.3	***	[4.6 ; 8.0]

*Note: *p < 0.1; **p < 0.05; ***p < 0.01; Significance and 95% confidence intervals (in parentheses) were obtained through a bootstrap procedure.*

Table 3: Impacts on land use under the D^{+} and D^{++} scenarios. Results are expressed as average percentage variations over the baseline.

	Baseline (ha)	D^{+}			D^{++}		
Hay Crops	20905	-0.6	***	[-0.9 ; -0.3]	-2.0	***	[-3.1 ; -1.0]
Alfalfa	5195	-3.2	***	[-4.5 ; -1.9]	-5.4	***	[-8.0 ; -2.8]
Ryegrass	*456*	*3.5*	*	[-0.1 ; 7.1]	*9.4*	***	[4.3 ; 14.5]
Others	*15255*	*-0.3*		[-0.8 ; 0.1]	*-2.4*	***	[-3.7 ; -1.2]
Silage Crops	5408	-2.6	***	[-3.5 ; -1.7]	-11.4	***	[-14.0 ; -8.7]
Silage Maize	*4426*	*-4.5*	***	[-5.8 ; -3.1]	*-18.4*	***	[-22.1 ; -14.7]
Others	982	1.0	**	[0.3 ; 1.7]	5.7	**	[1.4 ; 10.0]
Grain Crops	3724	-1.8	**	[-3.0 ; -0.7]	-11.2	***	[-14.4 ; -8.1]
Pastures	15915	0.1	**	[0.0; 0.3]	0.4	**	[0.1; 0.8]

*Note: *p < 0.1; **p < 0.05; ***p < 0.01; statistical significance and 95% confidence intervals (in parentheses) were obtained through a bootstrap procedure.*

Table 3: Impacts on economic outcomes and resource use under the D^{++} drought scenario combined with feed price increases (FP15, FP25, FP50). Results are expressed as average percentage variations over the baseline.

	FP15			FP25			FP50		
Operating Income	-10.8	***	[-14.2 ; -7.4]	-16.3	***	[-21.0 ; -11.6]	-24.8	***	[-30.6 ; -19.0]
Work	-11.0	***	[-12.1 ; -9.9]	-14.7	***	[-16.0 ; -13.5]	-21.8	***	[-23.3 ; -20.2]
Water	1.7	***	[1.2 ; 2.1]	2.0	***	[1.5 ; 2.6]	2.3	***	[1.7 ; 3.0]
Groundwater	*0.9*	***	[0.5 ; 1.2]	*1.1*	***	[0.7 ; 1.6]	*1.3*	***	[0.8 ; 1.9]
Land	-0.4		[-1.5 ; 0.8]	0.7		[-0.5 ; 1.9]	2.3	***	[0.9 ; 3.8]
Irrigated Land	-6.4	***	[-7.6 ; -5.1]	-6.2	***	[-7.4 ; -4.9]	-5.9	***	[-7.2 ; -4.6]
Nitrogen	-2.9	***	[-3.9 ; -1.9]	-2.4	***	[-3.5 ; -1.4]	-2.2	***	[-3.4 ; -1.0]
LSU	-14.8	***	[-15.7 ; -13.8]	-20.9	***	[-22.2 ; -19.7]	-32.4	***	[-34.0 ; -30.8]
Feed	-29.5	***	[-31.7 ; -27.3]	-42.0	***	[-44.4 ; -39.6]	-62.7	***	[-65.2 ; -60.1]

*Note: *p < 0.1; **p < 0.05; ***p < 0.01; statistical significance and 95% confidence intervals (in parentheses) were obtained through a bootstrap procedure.*

Table 3: Impacts on land use under the D^{++}drought scenario combined with feed price increases (FP15, FP25, FP50). Results are expressed as average percentage variations over the baseline.

	FP15			FP25			FP50		
Hay Crops	5.4	***	[3.9 ; 6.9]	8.4	***	[6.5 ; 10.4]	13.8	***	[11.0 ; 16.6]
Alfalfa	4.3	.	[-0.2 ; 8.8]	9.9	***	[3.1 ; 16.6]	22.0	***	[10.6 ; 33.3]
Ryegrass	*41.6*	.	[-1.1 ; 84.3]	*56.0*	**	[3.9 ; 108.1]	*86.2*	**	[15.9 ; 156.4]
Others	*4.6*	***	[2.8 ; 6.4]	*7.0*	***	[5.0 ; 9.1]	*11.4*	***	[8.4 ; 14.4]
Silage Crops	-6.3	***	[-10.0 ; -2.6]	-6.0	***	[-9.9 ; -2.0]	-2.5		[-8.3 ; 3.2]
Silage Maize	*-14.0*	***	[-18.3 ; -9.7]	*-11.2*	***	[-15.8 ; -6.6]	*-9.2*	***	[-14.3 ; -4.2]
Others	13.5	**	[3.7 ; 23.2]	12.8	**	[2.2 ; 23.4]	14.9	**	[0.4 ; 29.3]
Grain Crops	-13.8	***	[-17.5 ; -10.2]	-14.6	***	[-18.5 ; -10.6]	-18.4	***	[-22.9 ; -14.0]
Pastures	-8.5	**	[-13.3 ; -3.7]	-14.6	***	[-20.2 ; -9.0]	-20.3	***	[-27.5 ; -13.1]

*Note: *p < 0.1; **p < 0.05; ***p < 0.01; statistical significance and 95% confidence intervals (in parentheses) were obtained through a bootstrap procedure.*

4. Discussions

This study assesses the impact of increasing levels of drought pressure and crop irrigation water requirements on dairy cattle farms' economic outcomes, land, and resource use, leveraging climatic data, FADN microeconomic information, and the AGRITALIM model. Under the strongest drought scenario, the additional impacts of feed price increases are jointly analyzed.

Results show that under drought pressure, farm operating income slightly reduces as farmers prioritize herd maintenance and increase their reliance on the market for feed requirements. Indeed, rather than long-term strategies, farmers usually rely on temporary crop strategies, also considering their knowledge of past climatic events and their expectations for future conditions (Holman et al., 2021). Under moderate drought (D^{+}), farms respond by reducing irrigated land and shifting towards less water-intensive crops, i.e., hay crops, while slightly reducing silage and grain crops, as well as increasing their feed purchases. This allows them to reduce the overall water use and maintain forage production with minimum impact on livestock. However, under severe drought (D^{++}), the water intensity increases although water-demanding crops like silage maize and grain crops are sharply reduced, reflecting the concentration of production on a smaller cultivated area. This leads to a stronger reliance on purchased feed to sustain herd size and exposes farms to risks related to feed availability and price volatility (Godde et al., 2021), highlighting the relevance of on-farm production and supply sources diversification to avoid over-reliance on specific regions (Solazzo et al., 2023). In other words, under moderate drought, crop substitution and water use reduction are sufficient to buffer impacts. Instead, under severe drought, these strategies are insufficient, forcing farms to rely on the market. Indeed, when feed prices increase under severe drought conditions, farms can no longer compensate through market purchases. Consequently, LSU and income decline, while purchased feed decreases proportionally to price increases. This suggests that the interaction between climate and market stress can produce non-linear effects that are more severe than single-factor scenarios. Farms also reduce costs by cutting the work employed on the farm, with social implications in areas where agriculture is a major source of employment and where skilled labor is crucial, i.e., in PDO production systems (Arfini et al., 2019). At the same time, they intensify production by reducing areas dedicated to pastures, reflecting an attempt to satisfy the cattle's nutritional needs through on-farm production. Moreover, irrigation intensity is higher under the feed price simulations, especially when groundwater extraction is possible, since it allows for greater flexibility in water supply (Gómez and Pérez Blanco, 2012). However, this strategy not only has negative environmental consequences in the long term (Baniasadi et al., 2020) but may also prove unfeasible, as higher irrigation demand and increasing water scarcity can create a vicious cycle (Baniasadi et al., 2020; Gorguner and Kavvas, 2020; Wada et al., 2010).

The land use strategy shifts from relying more on rainfed crops to maintaining on-farm production, especially for silage crops, whose area reduction is inversely proportional to the increase in feed prices. At the same time, farms try to rely more on crop alternatives such as barley and triticale, because maize remains one of the most affected by drought (Buttinelli et al. 2026; Mereu et al., 2021). At the same time, they increase reliance on alfalfa, which is crucial to satisfy the protein requirement in the dairy cattle diet.

Although average impacts appear limited, the results show a high heterogeneity across farms: even if the overall average impacts, especially under D^+, appear small, the sample shows a high variability in the magnitude of these impacts. This suggests that strategies like replacing water-intensive crops with less intensive ones may not guarantee uniform protection. This heterogeneity reflects the diversity in cropping mixes and production intensity across farms. Overall, the picture is of a sector able to cope with drought stress in the short term if able to rely on the market for feed supply. In terms of land use and impacts on cultivated crops, dairy cattle farms in Italy are able to maintain herd size and protect their income through increased reliance on the market if prices remain stable. However, when feed prices increase, the combination of drought and higher costs makes them more vulnerable and forces them to increase irrigation water and production intensity, and reduce costs related to work. Yet, this strategy results in substantial income and production losses, given the difficulties of substituting purchased feed with on-farm production in the context of water shortages.

The study has some limitations. First of all, it assumes constant water and feed market availability, potentially underestimating total impacts. Increasing water scarcity and the priority allocation of water to domestic and industrial sectors during periods of shortages (Wada et al., 2010), as well as feed shortages or quality deterioration, could worsen the estimated impacts, especially for PDO productions, through compounding effects not captured here. Second, crop quality deterioration and increased sanitary risks associated with water stress (Le Gouis et al., 2020; Medina et al., 2015; Wu et al., 2010), and the negative impacts of heat stress on animals are not considered. Indeed, direct impacts on milk yields, quality, and cattle mortality are not evaluated, even though climate change is known to negatively affect the performance of dairy farms by altering these characteristics (Wankar et al., 2021, Quiedeville et al., 2022). This modelling choice reflects the extent of the analysis as AGRITALIM operates on a national representative sample, encompassing heterogeneous agro-climatic zones, production systems, breeds, productivity levels, and PDO productions. While it is feasible in case-study analyses, estimating direct impacts on animals at the national level is complex and would require strong generalizations. Furthermore, a reduction in milk production could also lead to higher milk prices, partially offsetting some losses, but this depends on global market conditions and is not analyzed here. Finally, the CAP 2023-2027 reform could introduce additional uncertainty (Baldi et al., 2024), due to the internal convergence process (Pierangeli et al., 2023, 2025) and the implementation of Eco-Scheme 1, which is specifically designed for livestock and aims to reduce antimicrobial use and promote grazing practices (Dell'Unto and Cortignani, 2025), partially hindered by the reduction of pastures emerging from the results.

5. Conclusions

The study highlights that dairy farms in Italy are able to cope with drought and increased crop water requirements in the short term if market conditions remain stable. They manage to minimize effects on income and maintain herd size, allocating resources efficiently in order to meet animals' nutritional requirements. However, this goal is met through increased reliance on the market for feed supply, making these farms exposed to market volatility. The combination of severe drought and increased feed prices reveals that the sector is not able to cope with feed shortages with on-farm production under critical climate conditions. This has serious economic, productive, environmental, and social consequences, such as increased production intensity and a reduction in employment. Moreover, further risks may arise if feed and forage supplies fail to meet demand or quality standards, especially for PDO cheese production.

Future research should explore how milk supply market responses, such as price adjustments, interact with production shocks. Moreover, integrating direct impacts on animals would provide a more comprehensive understanding of the challenges faced by the sector, allowing for the assessment of drought impacts on cattle's productive performance, mortality rates, and nutritional requirements. Finally, analyzing the role played by the CAP 2023-2027 reform in sustaining farms under stressful climatic conditions would enable an evaluation of the interaction between drought and policy design. This work is a first step towards an integrated assessment able to reveal the dairy sector's vulnerability under simultaneous climatic and market shocks and its reliance on external feed supplies, a factor potentially amplifying drought-related risks. Given the increasing frequency and intensity of such extreme events and the economic relevance of the dairy sector, this represents a critical challenge for the stability, sustainability, and quality of the broader Italian agri-food chain.

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