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Adoption of precision livestock farming devices in the dairy cattle sector: An assessment based on agroeconomic modelling

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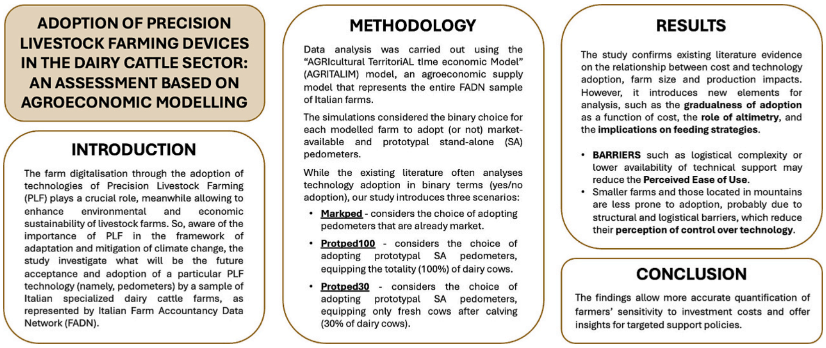
HIGHLIGHTS

- Farmers' decision to adopt PLF depends on the potential benefits they achieve
- Altimetric context adds an additional layer of complexity to PLF adoption decisions
- Structural and altimetric barriers influence perceived ease of use
- The adoption rate of PLF devices gradually increases with costs reduction
- EU can promote an equitable digital transition across diverse farming landscapes

GRAPHICAL ABSTRACT



ADOPTION OF PRECISION LIVESTOCK FARMING DEVICES IN THE DAIRY CATTLE SECTOR: AN ASSESSMENT BASED ON AGROECONOMIC MODELLING

INTRODUCTION

The farm digitalisation through the adoption of technologies of Precision Livestock Farming (PLF) plays a crucial role, meanwhile allowing to enhance environmental and economic sustainability of livestock farms. So, aware of the importance of PLF in the framework of adaptation and mitigation of climate change, the study investigate what will be the future acceptance and adoption of a particular PLF technology (namely, pedometers) by a sample of Italian specialized dairy cattle farms, as represented by Italian Farm Accountancy Data Network (FADN).

METHODOLOGY

Data analysis was carried out using the "AGRIcultural TerritoriAL tIme economic Model" (AGRITALIM) model, an agroeconomic supply model that represents the entire FADN sample of Italian farms.

The simulations considered the binary choice for each modelled farm to adopt (or not) market-available and prototypal stand-alone (SA) pedometers.

While the existing literature often analyses technology adoption in binary terms (yes/no adoption), our study introduces three scenarios:

- **Markped** - considers the choice of adopting pedometers that are already market.
- **Protped100** - considers the choice of adopting prototypal SA pedometers, equipping the totality (100%) of dairy cows.
- **Protped30** - considers the choice of adopting prototypal SA pedometers, equipping only fresh cows after calving (30% of dairy cows).

RESULTS

The study confirms existing literature evidence on the relationship between cost and technology adoption, farm size and production impacts. However, it introduces new elements for analysis, such as the **gradualness of adoption** as a function of cost, the **role of altimetry**, and the **implications on feeding strategies.**

- **BARRIERS** such as logistical complexity or lower availability of technical support may reduce the **Perceived Ease of Use**.
- Smaller farms and those located in mountains are less prone to adoption, probably due to structural and logistical barriers, which reduce their **perception of control over technology**.

CONCLUSION

The findings allow more accurate quantification of farmers' sensitivity to investment costs and offer insights for targeted support policies.

ARTICLE INFO

Keywords:
Climate change
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ABSTRACT

This study investigates the potential adoption of pedometers as a Precision Livestock Farming (PLF) technology in Italian dairy cattle farms, using data from the Italian Farm Accountancy Data Network (year 2021).[1] Two types of pedometers - market-available and prototypal stand-alone (SA) - were evaluated through simulations performed with the AGRITALIM agroeconomic model. Results indicate that adoption rates relevantly increase as the cost of investment needed reduces, up to exceeding 50 % of the sample farms in the case of SA pedometers. Moreover, adoption is higher in large, intensive farms located in plains, while those in mountainous and hilly areas face challenges related to infrastructure and cost-effectiveness of the investments. These findings highlight the importance of context-specific support mechanisms within Common Agricultural Policy measures to facilitate PLF adoption in diverse farming conditions and to increase the number of livestock farms engaged in climate change mitigation and adaptation actions.

1. Introduction

A key objective of 2023–2027 Common Agricultural Policy (CAP) for EU livestock sector pertains improving animal welfare, while ensuring economic, social and environmental sustainability of farming activities (Buschmann et al., 2023). This ambitious goal reflects a growing

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recognition of the interconnection among animal welfare, environmental protection, and farm profitability (Röder et al., 2024). In formulating its national CAP Strategic Plan, Italy has outlined specific measures designed to incentivize farmers to prioritize and improve animal welfare (Runge et al., 2022). In particular, Eco-Scheme 1 and Action 30 of Rural Development for the Environment stand out as targeted initiatives aimed at achieving this objective. Eco-Scheme 1 provides financial incentives to farmers who adopt practices and systems that advance animal welfare standards beyond the baseline regulatory requirements. Similarly, Action 30 offers payments to farmers who commit to environmentally sustainable practices that also align with improved welfare outcomes for livestock. To effectively meet these European targets, relevant investments in technology will be essential (Matthews, 2021). In this context, farm digitalisation through the adoption of technologies of Precision Livestock Farming (PLF) plays a crucial role, meanwhile allowing to enhance environmental and economic sustainability of livestock farms (Himu and Raihan, 2024; Selvaggi et al., 2024a).

The integration of PLF technologies offers multiple direct benefits. From an animal welfare perspective, these tools allow for early detection of health issues, reducing stress and suffering through timely interventions (Berckmans, 2017). For instance, wearable sensors can monitor vital signs and behaviour patterns, alerting farmers of potential problems such as illness, injury, or suboptimal living conditions (Rutten et al., 2013). Particularly in cattle farms, this allows prompt and effective actions to be undertaken, possibly reducing the administration of veterinary drugs and avoiding production losses (Dominiak and Kristensen, 2017; Morrone et al., 2022). In addition to health monitoring, PLF technologies contribute to animal welfare by improving housing conditions in line with animals' physiological and behavioural requirements. Precision management of environmental parameters such as temperature, ventilation, and lighting helps to minimize discomfort and stress, while continuous tracking of activity and mobility facilitates the early detection of lameness and supports the expression of natural behaviours. In parallel, PLF also enhances productivity and economic performance. Automated feeding systems deliver individualized nutrition according to specific needs of each animal, improving feed efficiency and overall health (Caro et al., 2016). These tools enhance environmental sustainability by minimizing resource use and waste, improving feed efficiency, and reducing nutrient losses and greenhouse gas emissions. These systems are often integrated with automated milking systems in milking robots, which are also able to perform a real-time analysis of individual milk yield and characteristics. Again, empirical evidence suggests that a prompt recognition of returning to heat after calving may allow to shorten calving interval, identifying the optimal period for insemination and improving the pregnancy rate. This makes it possible to reduce the incidence of unproductive periods in the career of dairy cows, limiting cows' infertility. The latter generates income losses from reduced milk production, higher costs for feeding and for artificial inseminations, increased labour employment, and delayed calving (Tekin et al., 2021). Thus, the possibility of monitoring reproductive conditions of dairy cows (especially at grazing, thanks to the real-time localization of the cows) allows to optimize management strategies and labour organization (Saint-Dizier and Chastant-Maillard, 2018).

All this might lead to substantially improve farmers' decision management, with positive effects also on farm economic outcomes (Frost et al., 1997; Defrancesco et al., 2008). By optimizing resource use and improving herd health, farmers can achieve higher yields and better-quality outputs. Moreover, the reduction in veterinary and feed costs, coupled with enhanced marketability of animal products that meet high welfare standards, can improve farm profitability (Selvaggi et al., 2024b). So, PLF increases farm resilience by lowering production risks, reducing veterinary costs, and improving product quality and efficiency.

These benefits can prove pivotal in fostering the adaptation of livestock systems to Climate Change (CC), particularly in the case of dairy cattle. The main impacts of CC on dairy cattle are related to the increase in the frequency and intensity of heat-stress-related phenomena, responsible for relevant production and economic losses (Polsky and Von Keyserlingk, 2017). By improving cattle health, welfare conditions and farm efficiency, PLF technologies can counteract these negative impacts, thereby strengthening the economic resilience of farms.

From an environmental perspective, the adoption of PLF technologies also generates indirect but relevant benefits. Improved animal health and resource efficiency lead to a reduction of Carbon Footprint of livestock products (Papakonstantinou et al., 2024) and to better socio-economic performance indicators (Lovarelli et al., 2023), while also contributing to the mitigation of greenhouse gas emissions (Kipling et al., 2019). Automation further enhances energy efficiency by reducing the need for manual labour and optimizing the use of resources such as feed, water, and electricity (Kaledio et al., 2023). For example, automated control devices inside the barns help regulate ventilation and lighting, minimize resource waste and lowering energy consumption, resulting in both economic savings and reduced environmental pressure (Tullo et al., 2019). Moreover, efficiency gains such as increased milk production per unit of input result in a lower environmental impact per animal (Balaine et al., 2020). So, a wider global adoption of PLF plays a significant role in reducing the environmental footprint of livestock production (Pirlo and Lolli, 2019), while simultaneously enhancing economic resilience, aligning the sector with sustainability and climate adaptation goals (Pardo et al., 2022).

Although the economic, environmental and social sustainability nexus is well addressed by the PLF approach (Lovarelli et al., 2020), the adoption of PLF technologies is influenced by a range of factors, including economic issues, technological usability, and perceived benefits (Bianchi et al., 2022). Among these factors, the cost of technology plays a pivotal role, as it can significantly impact farmers' willingness to invest in innovative solutions (Odintsov Vaintrub et al., 2021). Several theoretical frameworks, such as the Technology Acceptance Model (TAM) (Davis, 1989) and the Theory of Planned Behaviour (TPB) (Ajzen, 1991), underline the importance of perceived ease of use, perceived usefulness, and behavioural intention in shaping technology adoption. Moreover, PLF adoption is strongly influenced by the specific context of each farm. These technologies are currently adopted mainly in large and intensive livestock systems, particularly indoor, due to the more frequent presence of conditions and facilities which make digitalisation easier (Aquilani et al., 2022), and to the possible influence of economies of scale which might obstacle PLF adoption in smaller systems (Rojo-Gimeno et al., 2019). Furthermore, farmers' decision to adopt PLF technologies, bearing the related investment and operating costs, depends on the value of the potential benefits they achieve with respect to their non-adoption, which in smaller farms might not justify such investments. In addition, the adoption of PLF technologies can also vary significantly based on the farm's geographical and altimetric characteristics. Farms located in mountainous or hilly areas often face additional challenges that may hinder PLF implementation (Morgan-Davies et al., 2017), such as reduced accessibility, fragmented land parcels, and limited availability of flat terrain suitable for infrastructure development. In contrast, farms situated in plains generally benefit from more favorable conditions for setting up digital systems, including easier installation of sensors and automated machinery. The altitude itself may also influence livestock management practices (Wishart et al., 2015) and, consequently, the potential for digitalisation, as harsh climatic conditions or seasonal accessibility issues may limit the feasibility or profitability of high-tech investments. Therefore, the altimetric context adds an additional layer of complexity to PLF adoption decisions, particularly for small or marginal farms where cost-effectiveness is more challenging to achieve.

To ensure that these benefits are accessible across diverse farm types and regions, financing mechanisms should be designed to be scalable and inclusive. In particular, the financial incentives provided through CAP measures could further reinforce the economic viability of adopting these advanced technologies (Guyomard et al., 2023). This implies a mix of direct grants, low-interest loans, and tax incentives tailored to farm size and orographic context, complemented by training and technical support.

So, aware of the importance of PLF in the framework of adaptation and mitigation of climate change, we investigate what will be the future acceptance and adoption of a particular PLF technology (namely, pedometers) by a sample of Italian specialized dairy cattle farms, as represented by Italian Farm Accountancy Data Network with reference to the year 2021. Two types of pedometers were considered in the analysis: i) market – available pedometers, that require the installation of a connectivity infrastructure on farm; ii) prototypal Stand – Alone (SA) pedometers. Pedometers are one of the most important devices available to dairy farmers as precision technologies. These are the most frequently studied sensor systems used to detect estrus (Madkar et al., 2022) and locomotion problems (Marques et al., 2024). Pedometers are digital tools that keep track of the number of steps that cows take over a set time (Shepley et al., 2017). Typically, data from pedometers are able to predict estrus, because in this status cows walk two to four times more than a non-estrus cow (Gaillard et al., 2016). The detection of estrus has great importance since its recurring cadency enhances the chance that the cow becomes pregnant (Galon, 2010). Nevertheless, these devices, along with collars equipped with various sensors (e.g., for detecting body temperature and rumination time), can be useful also for checking animal health and welfare conditions.

The present study builds on the results of the simulations performed through a supply side agroeconomic model (AGRITALIM). The simulations considered the binary choice for each modelled farm to adopt (or not) market – available and prototypal SA pedometers. In the latter case, the possibility of equipping with prototypal SA pedometers the totality (100 %) of dairy cows and only fresh dairy cows after calving (30 %) was considered in two distinct simulations. The results obtained highlight that the share of adoption of market – available and prototypal SA pedometers, keeping equal the benefits in terms of productivity gains (shortening of calving interval and reduction of the quota of other cattle with respect to productive cows), greatly depends on the cost of investment. The latter is lower adopting prototypal SA pedometers in particular when only fresh dairy cows after calving (30 %) are equipped with. Thus, the share of adopting farms is the highest in this case. Furthermore, it emerges with evidence that largest farms and farms operating in plain areas (i.e., more intensive and profitable farms) would be in any case more likely to adopt pedometers.

The remainder of the paper is articulated as follows. In the Materials and Methods section, the main characteristics of 2021 FADN sample of Italian specialized dairy cattle farms are analysed and some techno – economic indicators pertaining both production and economic scale and performance of the farms are presented; for articulating this description, farms are distinguished by classes of herd size and altimetry of their location. Then, the simulations performed are described, along with the characteristics of prototypal SA pedometers and the benefits considered achievable from the adoption of pedometers (in our hypothesis, identical between market – available and prototypal SA pedometers), as well as the features of the AGRITALIM model. The Results section opens comparing the value of techno – economic indicators between groups of farms adopting or not the pedometers under the simulations performed. Then, again distinguishing farms by herd-size and altimetry classes, the share of farms adopting pedometers in each simulation is shown, along with the subsequent production and economic impacts. Results are discussed in the Discussion section, followed by the Conclusions section, drawing policy implications.

2. Materials and methods

2.1. Sample description – Farm Accountancy Data Network (FADN)

Table 1 reports the main characteristics of FADN sample with reference to Italian specialized dairy cattle farms (year 2021). A distinction across the sample was performed by herd-size and altimetry classes. Herd-size classes were obtained by dividing the sample of modelled farms into quartiles, based on the number of livestock units (LSU) reared at the baseline (1: $\leq$24 LSU; 2: $>$24–47 LSU; 3: $>$47–102 LSU; 4: $>$102 LSU). The information reported pertain the number of farms, the amount of Operating Income (OI) generated, the quantity of feed purchased, the number Livestock Units (LSU) reared distinguishing by cows and other cattle, as well as the quantity of milk produced.

Table 1
Number of farms, baseline distribution of OI, purchased feeds, LSU and milk production among the different herd-size and altimetry classes (whole sample).

	Farms	OI	Feed purchase	Cows	Other cattle	Milk production
	n	*EUR,000*	*t*	*n*	*n*	*t*
		Herd-size classes				
1	191	1237	80	1796	920	9564
2	191	3534	214	4373	2134	23,916
3	190	7809	491	8888	4160	57,118
4	191	36,349	2080	31,279	17,409	245,562
		Altimetry classes				
Mountain	419	10,206	715	12,869	6151	78,747
Hill	164	12,173	836	12,212	5910	87,155
Plain	180	26,551	1314	21,254	12,562	170,258
		Total				
	763	48,930	2865	46,336	24,623	336,160

Source: own elaboration.

About 70 % of production activities take place in farms falling in the highest quartile, which generate a more than proportional share (nearly 75 %) of sample OI, thus denoting that these farms are characterised by the highest level of profitability of rearing activities. Such shares reach 85–90 % including also the third quartile. As regards altimetry classes, nearly 50 % of production activities are carried out in farms operating in plain areas (representing 23.6 % of the sample), which generate a more than proportional share (nearly 55 %) of sample OI (indicating that the highest level of profitability characterises these farms). These shares reach about 75 % of production activities and nearly 80 % of OI including also the farms operating in hilly areas (themselves representing 21.5 % of the sample). Thus, it emerges a concentration of the volume of production activities and OI in the higher α-quantile and in non-mountain farms, characterised by higher productivity and profitability of rearing activities.

Table 2 reports the median[2] value of some techno-economic indicators describing the farms in the different herd-size and altimetry classes, and overall. These indicators pertain both production and economic scale (OI; LSU; acreage of utilized agricultural area, UAA) and performance (OI per LSU, OI/LSU; hours of labour employed per LSU, L/LSU; value of feed purchased per LSU, FP/LSU; amount of concentrate feed in the ration, CF:C; daily milk yield per cow, DMY).

As regards herd-size classes, rearing intensity and productivity increase with production and economic scale. OI/LSU is significantly greater in the higher α-quantile than in the lower quartiles, indicating better economic performances. This is made possible by higher values of DMY, though this makes higher amounts of concentrate feeds in the ration necessary (evidenced by significantly higher values of CF:C and FP/LSU). The lower L/LSU in the higher α-quantile also suggests a higher level of mechanization and automation of production activities.[3]

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[2] An analysis performed through the Shapiro-Wilk test ($p \leq 0.05$) allowed us to assess the non-normal distribution of the value of indicators across the sample.

[3] FADN data do not report information on the uptake of digital technologies by sampled farms.

Table 2
Median value of the descriptive indicators at baseline for the different herd-size and altimetry classes.

	OI		LSU		UAA		OI/LSU		L/LSU		FP/LSU		CF:C		DMY	
	EUR		*n*		*Ha*		*EUR/n*		*h/n*		*EUR/n*		*%*		*l cow-1 day-1*	
	Herd-size classes															
1	3201	d	15	d	10	d	278	b	140	a	579	b	25.1	c	14.4	c
2	15,154	c	34	c	21	c	438	b	85	b	646	b	25.4	c	13.9	c
3	35,985	b	67	b	30	b	556	a	51	c	726	a	27.8	b	17.7	b
4	119,577	a	190	a	60	a	570	a	24	d	775	a	29.7	a	21.6	a
	Altimetry classes															
Mountain	13,701	c	32	c	21	c	405	b	95	a	666	b	25.9	b	14.6	b
Hill	28,763	b	57	b	28	b	566	a	51	b	711	a	27.1	a	17.3	b
Plain	75,902	a	141	a	38	a	574	a	33	c	670	b	28.5	a	21.2	a
	Total															
	23,798		47		26		494		66		674		27.0		16.6	

The differences among groups in herd-size classes and geographical areas were tested for $p \leq 0.05$ (Kruskal-Wallis Test and Dunn's Pairwise Comparison Test).
Source: own elaboration.

Similar considerations can be draft considering altimetry classes. Farms operating in plain areas are characterised by the largest production and economic scale, highest DMY (and CF:C), OI/LSU and lowest L/LSU. Production and economic scale, as well as rearing intensity and economic performance gradually decrease shifting toward hill and mountain farms. Looking at the FP/LSU indicator, the highest value pertains farms operating in hilly areas, while farms located in mountain and plain areas present non-differing values.

2.2. Simulations performed

Three simulations were conducted using the farms recorded in 2021 FADN sample of Italian specialized dairy cattle farms, with reference to the choice of adopting market – available or prototypal SA pedometers, as outlined in Table 3.

i. *Markped*:

This simulation considers the choice of adopting pedometers that are already market – available. This choice involves bearing an investment cost for digital infrastructure (EUR 50,000, independently from the number of cows reared), as well as an investment cost of EUR 100 per cow for purchasing pedometers and casings (all one with pedometers), with a duration of seven years and no cost for assistance and maintenance during the years of duration of the investment.

Table 3
Costs and duration of the investments for adopting market and prototypal pedometers under the three simulations performed.

		Market pedometers (*Markped*)	Prototypal pedometers (*Protped100*)	Prototypal pedometers (*Protped30*)
Cost for digital infrastructure	EUR	50,000	0	0
Cost for pedometers	EUR/cow	100	150	150
Cows equipped with pedometers	%	100	100	30
Cost for pedometer casings[1]	EUR/cow	0	30	30
Cows equipped with casings	%	100	100	100
Costs for assistance and maintenance	EUR/year	0	1500	1500
Duration of investments	Years	7	5	5

Source: own elaboration.

[1] Market pedometers include casings.

ii. *Protped100*:

This simulation considers the choice of adopting prototypal SA pedometers, equipping with the pedometer and the casing (not included in pedometers' purchase) the totality (100 %) of dairy cows. This choice involves bearing no investment cost for digital infrastructure, an investment of EUR 180 per cow and a yearly cost of EUR 1500 for assistance and maintenance during the five years of duration of the investment.

iii. *Protped30*:

This simulation considers the choice of adopting prototypal SA pedometers, equipping with the pedometer only fresh cows after calving (30 % of dairy cows) and with the casing (not included in pedometers' purchase) the totality (100 %) of dairy cows. This choice involves bearing no investment cost for digital infrastructure, an investment of EUR 150 per cow equipped with the pedometer, an investment of EUR 30 per cow for the casing and a yearly cost of EUR 1500 for assistance and maintenance during the five years of duration of the investment.

As evidenced in the description of the scenarios, the simulations *Protped100* and *Protped30* do not differ for the technology under consideration (prototypal SA pedometer with casing to be purchased apart), but for the quota of dairy cows equipped with pedometers (100 % in *Protped100* and 30 % in *Protped30*), while in both cases 100 % of dairy cows have to be equipped with the casing. The reason for performing two different simulations with the same technology lies in the fact that equipping all dairy cows with prototypal pedometers, as in the case of market – available pedometers, allows a continuous monitoring of them, with a possible improvement of animal health and welfare.[4] This is not achievable equipping only fresh cows after calving, with the only purpose to promptly recognize their returning to heat after calving for reducing calving interval.

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[4] Production and economic benefits deriving from the improvement of animal health and welfare conditions could not be quantified, thus these benefits were not considered in the present study.

2.3. Background information about prototypal SA pedometer

The prototypal SA pedometer was developed in the framework of a research project financially supported by the European Commission. It has been developed choosing recyclable and biocompatible materials in compliance with the aims of the Green Deal (Porto et al., 2023). Contrasting pedometers already available on the market, the prototypal device does not need any IT and technical facilities on the farm, but works by downloading information to a router already routinely present in the barn. This represents a great novelty for farmers because they do not need to infrastructure their barn with costly investments. Moreover, each device is autonomous and there is not a minimum number of devices to install. So, farmers can purchase individual low-cost pedometers, according to their needs.

A further innovative feature of the prototypal SA pedometer is that it consists of two modules: an external casing to protect the inner capsule containing hardware and software for data analysis (Bonfanti et al., 2022). The internal unit is removable, interchangeable and modular. Thanks to a very simple paw anchoring system, the farmers can easily move the internal capsule from one cow to another. The casing (without any electronical components) is expected to be installed on all cows in the barn, while the capsule is to be used only on the cows that the farmer will inseminate in the month after the installation. The capsule is the most expensive module of the device, and this chance of install as needed has a positive economic impact: this reduces the number of capsules that each farmer needs to have on farm, parameterized to the average number of animals to be inseminated monthly.

2.4. Benefits considered achievable from the adoption of pedometers

In the hypotheses followed for the present study, the benefits achieved by modelled farms from the adoption of pedometers are identical between market – available and prototypal SA pedometers. Such benefits consist in the possibility of shortening the length of calving interval by 21 days thanks to the prompt recognition of the first returning to heat after calving in reared dairy cows. This allows to increase the quota of productive dairy cows in the herds and to reduce the quota of other cattle, by a measure that should depend on the baseline duration of calving interval in each modelled farm. However, information on herd management like this are not provided by the FADN database, so it was necessary to integrate with the information provided at territorial level on the length of calving interval by the annual bulletin of the Italian Breeders Association with reference to the year 2021.[5] The duration of calving interval has wide variability among the different territorial areas of Italy (depending on cattle breed composition and management, climate conditions, etc.), ranging from 391 days in the North – West to 408 days in the South. Considering this variability, a coefficient (MC_n) was calculated at territorial level and multiplied by the ratio between productive cows and other cattle characterising each modelled farm.[6]

2.5. The AGRITALIM model

Data analysis was carried out using the "AGRIcultural TerritoriAL tIme economic Model" (AGRITALIM) model, an agroeconomic supply model that represents the entire FADN sample of Italian farms, already used in previous studies to simulate the impacts of EU agriculture and environmental policy changes (Coderoni et al., 2024; Dell'Unto et al., 2023; Cortignani et al., 2022). The model uses a large part of FADN information on economic, financial, productive, market, political and structural aspects, distinguishing among geographical areas, altimetric levels and farm types. The model considers both short and medium-long term aspects. The short-term nature lies in the fact that farms cannot change their production orientation, sell or buy land, etc. However, the model has some dynamic elements, as it can consider structural changes (e.g., number of animals and related rearing areas) annualizing the investments made through depreciation rates. The general mathematical representation of the model is the following:

$$max_X = \boldsymbol{C}\,\boldsymbol{X}$$

$$s.to\ \boldsymbol{A}\,\boldsymbol{X} \le \boldsymbol{B}\ [\lambda]$$

The model maximizes operating income at farm level based on the unitary income (***C***) of each production activity (***X***). The model is subject to constraints that bind resource requirements (land, labour, water, etc.) for each activity, specified in the technical coefficient matrix (***A***), to resource availability (***B***).

An advance was made implementing the model to endogenize the quantification of nutrient requirements and supply to dairy cattle, according to the nutritional system established by the French National Research Institute for Agriculture, Food and the Environment (INRA, 2018). The pre-existing feed constraint was replaced with the nutritional constraint specified in the following equation:

$$\sum_{ja} nr_{n,ja,nutr}{}^{*}XA_{n,ja} \le \sum_{j} XC_{j,n}{}^{*}yc_j{}^{*}nc_{j,nutr} + \sum_{f} XF_n{}^{*}nc_{f,nutr} \forall n, nutr$$

The nutritional constraint acts at farm level to balance each nutritional parameter (*nutr*: capacity of intake, metabolizable energy and protein). Here, $nr_{n,ja,nutr}$ represents animals' (*ja*) requirements for each nutritional parameter, varying among farms (*n*) based on milk yield and herd composition. Overall requirements have to be primarily satisfied with supply from crops (*j*) grown on-farm, based on the extension of the different crops ($XC_{j,n}$), crop yield (yc_j) and nutritional content of the corresponding feedstuff ($nc_{j,nutr}\mathrm{ns}_{\mathrm{j,nutr}}$). Possible shortages can be integrated through feed purchase (XF_n), choosing the best combination among a set of market-available feedstuffs with different nutritional content ($nc_{f,nutr}$).

In order to perform the simulations regarding the adoption of pedometers, the model was further implemented with a binary variable (BIN) allowing the individual farms to choice whether investing (BIN = 1) or not (BIN = 0), alternatively, in the two types of pedometers. An increase of the quota of productive cows on farm was simulated as a consequence of the adoption of pedometers, as specified in the additional constraint that follows:

$$XA_{n,ja_L} \le XA_{n,ja_{NL}} \times LNL_n \times (1 + MC_n \times BIN_n)$$

where XA_{n,ja_L} and $XA_{n,ja_{NL}}$ represent, respectively, the number of productive cows and other cattle (including dry cows, replacement heifers and growing cattle). Choosing to adopt pedometers ($BIN_n = 1$), each farm achieves an increase of the ratio between productive cows and other cattle (LNL_n) in a measure corresponding to the multiplying coefficient MC_n, with respect to non-adoption of pedometers ($BIN_n = 0$).

Finally, in order to evaluate the sole impact of adopting pedometers on herd composition, a further constraint was imposed in order to not allow any increase in the total number of cattle reared on farm.

3. Results

Table 4 reports the median value of the descriptive indicators already showed in Table 2, this time distinguishing among farms adopting (1) or non-adopting (2) pedometers under the three simulated scenarios.

Due to the characteristics of the simulated scenarios (Table 3), the cost of investment is the highest in the simulation *Markped*, intermediate in the simulation *Protped100*, while it is the lowest in the simulation *Protped30*. Thus, as expected, the share of the farms choosing to adopt pedometers gradually increases, from 11.1 % for market – available pedometers to 30.1 % for prototypal SA pedometers applied only on 30

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[5] Source: http://bollettino.aia.it/

[6] The values of the MC_n coefficients are the following: 0.073 (North – West), 0.0723 (North – East), 0.069 (Centre), 0.0685 (South), 0.0702 (Islands).

Table 4
Median value of the descriptive indicators at baseline for the groups of farms adopting/non-adopting pedometers under the simulations performed.

Simulation	Pedometers adoption	Farms		OI	LSU	UAA	OI/LSU	L/LSU	FP/LSU	CF:C	DMY
		N.	%	*EUR*	*n*	*ha*	*EUR/n*	*h/n*	*EUR/n*	*%*	*l* cow^{-1} day^{-1}
Markped	0	678	88.9	19,816	40	24	466	74	661	26.6	15.7
	1	85	11.1	141,222	224	61	743	24	809	30.7	23.3
Protped100	0	590	77.3	17,649	39	23	441	76	652	26.1	15.1
	1	173	22.7	62,688	100	42	632	40	786	30.1	21.1
Protped30	0	533	69.9	16,022	35	22	447	81	644	25.7	14.6
	1	230	30.1	56,280	100	43	556	41	784	30.1	20.5

All the differences are significant for $p \leq 0.05$ (Mann-Whitney *U* test and K-Sample Median Test).
Source: own elaboration.

% of dairy cows, passing through 22.7 % for prototypal SA pedometers applied to the totality of dairy cows. As a result, the gap in farm dimensions, rearing intensity and productivity, as well as in the economic performance, tends to reduce with the reduction of the cost of investment. Nonetheless, the characteristics of the farms in the groups adopting the pedometers are significantly different from those of farms in non-adopting groups: adopting farms are characterised by higher milk yields (DMY), larger recourse to purchased feeds (FP/LSU), in particular concentrates (CF:C), lower unit labour employment (L/LSU), higher unit profitability (OI/LSU), larger production (LSU, UAA) and economic (OI) scale.

Table 5 reports the share of farms adopting pedometers under the three simulations performed over the total number of farms operating in the different herd-size and altimetry classes.

As the cost of investment reduces, from the simulation *Markped* to *Protped30*, passing through *Protped100*, the overall number of farms adopting pedometers increases, as expected, from 11.1 to 30.1 %. In *Markped*, pedometers are not at – all adopted by farms in the lower herd-size classes, while the share of adoption reaches 5.8 % and 17.3 % under the simulation *Protped30*. Similarly, looking at the higher herd-size classes, this share increases from 8.9 % and 35.6 % to 37.9 % and 59.7 % respectively. Considering altimetry classes the same considerations can be made, confirming that a parallelism exists between the class of altimetry in which farms operate, their size and the level of convenience in adopting pedometers. As a result, the share of adoption of pedometers ranges from 3.8 % in *Markped* for mountain farms, to 48.3 % in *Protped30* in plain farms.

The next Table 6a–6c is subdivided into three parts and describes the impacts in terms of percentage variations over baseline values (reported in Table 3) on OI, quantity of feed purchased, LSU of cows and other cattle and quantity of milk produced under the different simulations performed (*Markped*, 6a; *Protped100*, 6b; *Protped30*, 6c).

Table 5
Total number of farms and share of farms adopting pedometers under the simulations performed, for the different herd-size and altimetry classes.

	Farms	*Markped*	*Protped100*	*Protped30*
	N.	Farms adopting (%)		
	Herd-size classes			
1	191	0.0	4.2	5.8
2	191	0.0	13.6	17.3
3	190	8.9	28.4	37.9
4	191	35.6	44.5	59.7
	Altimetry classes			
Mountain	419	3.8	16.9	22.9
Hill	164	11.6	22.0	28.7
Plain	180	27.8	36.7	48.3
	Total			
	763	11.1	22.7	30.1

Table 6a
Impacts (percentage variations) from the adoption of commercial pedometers (sim. Markped, whole sample).

	OI	Feed purchase	Cows	Other cattle	Milk production
	Herd-size classes				
1	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0
3	0.7	0.2	0.2	−0.3	0.3
4	3.5	1.4	1.6	−1.6	1.6
	Altimetry classes				
Mountain	0.8	0.2	0.3	−0.3	0.3
Hill	2.4	0.8	1.0	−1.2	1.0
Plain	3.6	1.6	1.7	−1.6	1.8
	Total				
	2.7	1.0	1.1	−1.2	1.3

Source: own elaboration.

Table 6b
Impacts (percentage variations) from the adoption of prototypal pedometers (sim. Protped100, whole sample).

	OI	Feed purchase	Cows	Other cattle	Milk production
	Herd-size classes				
1	0.4	0.2	0.2	−0.2	0.2
2	0.8	0.4	0.4	−0.5	0.5
3	2.7	0.8	0.9	−1.0	1.0
4	3.8	1.5	1.7	−1.8	1.8
	Altimetry classes				
Mountain	2.3	0.7	0.8	−0.9	0.9
Hill	2.9	0.9	1.2	−1.4	1.3
Plain	4.0	1.7	1.8	−1.8	1.9
	Total				
	3.3	1.3	1.4	−1.5	1.5

Source: own elaboration.

With equal benefits achievable from the adoption of pedometers under the three simulations performed, the extent of the impacts, overall and by herd-size and altimetry classes, grows as the share of adopting farms increases, as a result of the gradual reduction of the cost of investment. From one side, adopting pedometers allows farms to increase the quota of productive cows in the herd. Keeping constant daily milk yield per cow (DMY), this translates into an equal increase of milk production at farm level, which, however, makes a larger recourse to feed purchase also necessary, bearing the related costs. From the other side, pedometers allow to reduce the quota of other cattle categories in the herd, saving the related rearing costs, what adds to the benefits on OI of the increase in milk production. As a result, overall OI of the whole sample (which includes non-adopting farms) increases by 2.7 % under *Markped*, 3.3 % under *Protped100* and 4.2 % under *Protped30* simulation.

Table 6c
Impacts (percentage variations) from the adoption of prototypal pedometers (sim. Protped30, whole sample).

	OI	Feed purchase	Cows	Other cattle	Milk production
	Herd-size classes				
1	0.6	0.2	0.2	−0.2	0.3
2	1.2	0.5	0.5	−0.6	0.6
3	3.5	1.0	1.2	−1.4	1.2
4	4.8	1.7	2.1	−2.5	2.1
	Altimetry classes				
Mountain	3.1	1.0	1.1	−1.3	1.1
Hill	3.7	1.2	1.5	−1.9	1.5
Plain	4.9	1.9	2.2	−2.6	2.3
	Total				
	4.2	1.4	1.7	−2.1	1.8

Source: own elaboration.

The larger the share of adopting farms, the larger the increase in OI, with higher benefits for largest farms and farms located in plain areas, which increase their OI up to nearly 5 %.

4. Discussion

The results of the simulations performed through the AGRITALIM model show the potential share of adoption of pedometers by dairy cattle farms. This topic is of crucial importance since a wider adoption of PLF tools such as pedometers would lead to an improvement in animal welfare, productivity and profitability of livestock activities, and to a reduction in the environmental impact of the production processes in cattle farms. On overall, our study confirms existing literature evidence on the relationship between cost and technology adoption, farm size and production impacts. However, it introduces new elements for analysis, such as the gradualness of adoption as a function of cost, the role of altimetry, and the implications on feeding strategies.

Aligning with the existing literature, an interesting aspect is related to the cost and adoption of PLF technologies such as pedometers. Several studies have already shown that the adoption of innovative technologies in agriculture depends largely on the cost of the initial investment and the perceived economic benefits (Bianchi et al., 2022). The results of this study confirm this trend, showing that reducing the cost of pedometers leads to an increase in their adoption (from 11.1 % to 30.1 %), consistent with technology adoption models such as the TAM or the TPB.

Notably, this study aligns with TAM in several ways. For example, the results show that farms adopt pedometers primarily because they improve productivity and profitability (up to 5 % increase in OI). Increasing the proportion of productive cows and reducing costs associated with other livestock categories are clear perceived benefits, incentivizing adoption. In addition, the gradual increase in adoption of pedometers as the investment cost goes down shows that the perceived ease of access to the technology is a key factor. The lower adoption in mountain farms suggests that barriers such as logistical complexity or lower availability of technical support, though not considered in the present analysis, may reduce the Perceived Ease of Use (PEOU) that is a key aspect of TAM. With reference to TPB, this study confirms what Selvaggi et al. (2024a) stated, showing that dairy cattle farms adopt pedometers when they perceive a clear economic and production benefit (increased OI, increased milk productivity, reduced rearing costs). In addition, the study shows that the adoption of pedometers is prevalent in larger, plain farms, where there is likely to be greater exposure to the technology, in a context characterised by higher propensity to innovation. In mountainous areas, lower adoption could also result from a lower social pressure effect due to fewer high-tech farms. Finally, the gradual increase in adoption rate with the reduction in investment cost shows that the perception of control over adoption is linked to the availability of economic resources. Smaller farms and those located in mountains are less prone to adoption, probably due to structural and logistical barriers, which reduce their perception of control over technology.

In addition, our study confirms the trend that PLF devices are mainly adopted in larger farms. Previous studies (Palma-Molina et al., 2023; Gargiulo et al., 2018) have shown that larger farms with higher production efficiency are more likely to adopt precision technology tools, due to the ability to better amortize costs. So, policies should promote collaborative models, such as cooperatives or shared service centres, that enable smallholders to access PLF infrastructures collectively, thereby reducing individual costs and risks. Public–private partnerships may also play a key role in ensuring that technology providers, advisory services, and farmers are aligned in the adoption process. Moreover, monitoring and evaluation frameworks should be integrated into funding schemes to track welfare, environmental, and socio-economic outcomes, ensuring accountability and evidence-based adjustments over time. An indirect contribution of the policy to the diffusion of PLF in livestock farms could stem from the evidence that this management approach has the potential to increase consumers' acceptability of livestock productions (Lovarelli et al., 2020). Reward mechanisms could be politically encouraged in order to internalize the non-monetary benefits of PLF adoption in market price of livestock products (e.g., labelling systems), provided that consumers are adequately informed on the real extent of these benefits.

Regarding the effects of PLF devices, such as pedometers, on productivity and profitability of dairy cattle farms, past research (Selvaggi et al., 2024b) has shown that pedometers improve reproductive management, increasing the proportion of productive cows and reducing the costs associated with managing other livestock categories. Our results are consistent with this evidence, showing increased productivity index and OI growth of up to 5 % for adopting farms.

Regarding the contribution of this study to the existing literature, a first aspect to highlight concerns the gradualness of pedometer adoption within livestock farms. While the existing literature often analyses technology adoption in binary terms (yes/no adoption), our study introduces three scenarios with decreasing costs, showing how the adoption rate gradually increases. This approach allows more accurate quantification of farmers' sensitivity to investment costs and offers insights for targeted support policies. In particular, the financial incentives provided through CAP measures could further reinforce the economic viability of adopting advanced technologies (Guyomard et al., 2023). This requires a combination of instruments such as direct grants, low-interest loans, and tax incentives, tailored not only to farm size but also to orographic context, since farmers operating in mountainous or hilly regions often face higher production costs and structural constraints.

An additional aspect examined in this study concerns the differential impact of PLF devices across altimetry classes. No study has yet explored the relationship between altimetry and the adoption of PLF technologies. Our results suggest that mountain livestock farms are less inclined to adopt pedometers, likely due to their smaller size and lower economies of scale. This raises new questions about how to make technology accessible even in less favorable contexts, for example, through specific incentives.

Moreover, the effects of adopting PLF technologies such as pedometers on animal feeding strategies appear to be particularly interesting. While many studies focus on the effects of pedometers on fertility and productivity, our results highlight an increase in the use of purchased feed, suggesting that technology adoption could also influence feeding strategies. This aspect could be further explored in future studies to understand its implications for the economic and environmental sustainability of livestock farming.

A final interesting aspect is related to the contribution this study makes to economic theory. In particular, this study introduces new variables that could extend TAM theory, offering a more realistic view of the adoption of PLF in the dairy sector. Indeed, TAM theory assumes that Perceived Usefulness (PU) is mainly related to efficiency or productivity, but this study shows that technology adoption is strongly influenced by the cost of the initial investment. The adoption rate increases with cost reduction showing that cost influences the perceived usefulness of technology. This suggests that the TAM model could be expanded to include the direct economic factor as a moderator of PU in the agricultural context. Furthermore, TAM assumes that Perceived Ease of Use is related only to the technical complexity of the technology. However, this study shows that structural and geographic barriers (elevation, farm size) influence perceived ease of use. For example, farms in the plain adopt pedometers more readily than those in the mountains suggesting TAM could be expanded to include structural and geographic factors that affect perceived ease of use.

As regards the TPB model, this study expands it in some aspects. Specifically, TPB considers the three factors (Attitude toward the Behaviour, Subjective Norms and Perceived Behavioural Control) as static influences on the decision to adopt a technology. However, this study suggests that adoption occurs gradually and is dependent on economic and structural conditions. For example, adoption increases over time as costs are reduced and economies of scale increase. This could imply that the three factors of TPB could change over time based on external factors such as economic incentives or technological development. Consequently, including a time dimension in the TPB would view technology adoption as an evolutionary process and not a static decision.

5. Conclusions

The 2023–2027 CAP offers a strategic framework to advance animal welfare in the EU livestock sector, with Italian Eco-Scheme 1 and Action 30 serving as pivotal measures to incentivize farmers. The adoption of PLF technologies emerges as a cornerstone, enhancing animal welfare, sustainability, and economic resilience.

To ensure an inclusive digital transition, support measures should account for orographic differences across plains, hills and mountains. Tailored funding, including grants or tax incentives, is crucial to reduce the high initial costs of PLF adoption, particularly for small-scale farmers. Equally important are training and technical support to facilitate effective integration.

Ultimately, collaboration among policymakers, technology providers and agricultural institutions is essential to establish best practices and ensure that innovation benefits all regions, paving the way for a more sustainable and welfare-oriented livestock sector.

CRediT authorship contribution statement

D. Dell'Unto: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **R. Selvaggi:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **G. Pappalardo:** Writing – review & editing, Writing – original draft, Validation, Investigation, Conceptualization. **R. Cortignani:** Writing – original draft, Visualization, Validation, Supervision, Software, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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