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Using FADN Data to Estimate CO_2 Abatement Costs from Italian Arable Crops

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Abstract: The assessment of economic and environmental sustainability of agricultural systems represents a critical issue, which has been addressed in this work with a multi-objective programming model to explore the abatement costs (AC) of CO_2 for a set of representative contexts of Italian arable land agriculture. The study was based on the FADN-compliant Italian database RICA and estimates the abatement costs of CO_2 emissions in a short time horizon, using linear multi-objective programming and compromise programming. RICA data were used to quantify technical parameters of the model, adopting an innovative concept of a cropping scheme to simulate land-use adaptation. The study shows a quite diversified situation regarding income and emission levels per hectare across the Italian region and farm classes. A reduction of CO_2 emissions higher than 5 kg/ha at an AC lower than 1 EUR/kg is affordable only in seven regions, among which Abruzzo, Lombardy, and Puglia show the highest potential. Comparing the estimated abatement costs for CO_2 emissions with the corresponding European Trade System prices highlights a difference of 1 order of magnitude, proving that emission reductions for Italian arable crops still require research and innovation to lower adaptation costs.

Keywords: sustainability; agriculture; CO_2 emissions; FADN; multi-objective programming

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1. Introduction

Sustainability is a complex multi-dimensional concept that includes economic, social, and environmental dimensions. According to Ikerd [1], sustainable agriculture must preserve its productivity and usefulness to society in the long term. This implies that farm activities have to learn to become environmentally sound, resource-conserving, economically viable, and socially supportive [2]. Recently, interest has grown toward evaluating the effect of human activities on global climate change due to greenhouse gases (GHGs), most of them being ascribed to carbon dioxide (CO_2) emissions.

Since 2005, the European Union has set up the Emission Trading System (ETS) for GHG emissions to face climate change by reducing greenhouse gas emissions, which is a cornerstone of the EU's policy to combat climate change and its key tool for reducing greenhouse gas emissions cost-effectively. In 2015, the European Commission presented a legislative proposal to revise the ETS after 2020 [3]. The ETS is based on the "cap and trade" principle. To reduce emissions from industrial sectors, the EU has set a cap on greenhouse gas emissions generated by various industries. The cap is measured in European Union Allowance (EUA) emission units, where each EUA allows the emission of one MT of CO_2 equivalent in a calendar year. Thus, companies have a fixed amount of CO_2 emissions available, expressed in tradable EUA. Companies that pollute less than their total allowance can offer the units left on the market, while companies that pollute more can do so if they buy EUAs on the market. Over the years, the ceiling has been progressively lowered to reduce greenhouse gas emissions in the atmosphere. It will be gradually further reduced by increasing the pace of annual reductions in allowances to 2.2%, forcing industries to pollute less.

The ETS covers the sectors and gases, focusing on emissions that can be measured, reported, and verified with a high accuracy level. Even if this is not the case of agriculture, one challenging issue is represented by assessing the abatement of CO_2 emissions in the primary sector [4] to explore how agricultural practices could change, and the consequential costs for farmers.

This study focuses on arable crops, including cereals, oleaginous, proteinic, industrial, and horticultural crops. For these crops, CO_2 emissions can be mainly due to machinery, the usage of which varies considerably across cropping systems and areas. Farming systems based on arable crops have a higher capacity to quickly adapt to external stimuli than permanent crops and the livestock sector, which require high investments and a long time to change. Instead, arable crops can be easily converted to more environmentally friendly options, for instance, by shifting from irrigated maize or industrial tomatoes to rainfed cultivations in a fast land-use adaptation process, or growing more extensively and reducing input use and operations via technological change. All adaptations have environmental and economic impacts, which are generally conflicting; in the current market conditions, more environment-friendly solutions are usually less profitable.

Several frameworks have been developed [5,6] to figure out the relations between agriculture, the environment, and society. One of the most used conceptual frameworks is the Driver–Pressure–State–Impact–Response (DPSIR) framework [7]. DPSIR interprets agriculture as a "driving force" of the main environmental "pressures" (e.g., pollution, waste disposal), that in turn affects the "state" of the environment (i.e., physical, biological, chemical conditions), which impacts society (i.e., health, ecosystem, economy). Finally, impacts typically claim for "responses" from public policy and the market, producing rules affecting farmers' businesses, choices, and adopted techniques. Understanding how such responses may affect economic, social, and environmental sustainability has been previously investigated, as summarised in several review papers [8–11].

In Italy, the Institute for Environmental Protection and Research (ISPRA) provides the estimation and reporting of the National Inventory of greenhouse gas emissions, prepared using the Intergovernmental Panel on Climate Change (IPCC) Guidelines. According to the 2021 report on agriculture, GHG emissions' trend "from 1990 to 2019 shows a decrease of 17.3% due to the reduction of the activity data, such as the number of animals, the cultivated surface/crop production, the amount of synthetic nitrogen fertiliser applied, and the changes in manure management systems" [12]. Coderoni et al. [13] developed a methodology based on an adaptation of the IPCC approach at the farm level, using Italian FADN data to estimate a farm's agricultural greenhouse gas emissions. In a follow-up application, Baldoni et al. compared the Total Factor Productivity (TFP) with greenhouse gas (GHG) emissions at the farm level, focusing on a 2008–2013 panel of Lombardy farms [14,15].

CO_2 is the main greenhouse gas, and even though the agricultural sector is not the main producer due to its relevant role among GHGs, the analysis of agricultural sources of CO_2 and the related abatement costs is paramount.

This work aims to estimate the abatement costs of CO_2 emissions in a short time horizon, considering different arable systems in Italy and using a simulation model based on official data collected and maintained in the Rete di Informazione Contabile Agricola (RICA) database. RICA is the Italian database of farm accountancy data, compliant with the EU-wide Farm Accountancy Data Network (FADN) requirements.

FADN data have been applied in agro-environmental studies on how agriculture is related to GHGs, as reported in a review of farm-level sustainability indicators, focusing on CAP and FADN [16]. Such data have been used to assess a grassland strategy for farming systems in Europe to mitigate GHG emissions [17] and the impact of an EU-wide policy to expand grassland areas and promote carbon sequestration in soils [18]; the economic model of the Common Agricultural Policy Regionalized Impact (CAPRI) was applied in both of these studies. Another study applied data envelopment analysis (DEA) methodology to analyse the environmental performance of English arable and livestock holdings [19]. An empirical analysis applying multinomial logit models analysed Italian agriculture throughout 2003–2007 [20]. Other approaches using FADN data focused on the eco-efficiency of arable farms in rural areas [21], on agricultural eco-efficiency in Italian Regions [22], and on greenhouse gas emissions from conventional farms [23].

Multicriteria methods have been commonly applied to support energy and environmental policies [24–26] and agricultural resource management [27]. In this study, linear multi-objective programming (LMP) [28,29] and compromise programming [30] have been adopted since the requested quantitative data were available and the methodology is well established and widely applied. Todman and al. used a multi-objective optimisation algorithm with a crop production model that simulates environmental effects to identify trade-off frontiers and associated possibilities for agricultural management [31]. Zander et al. developed the MODAM, an instrument that can help mediate conflicts among competing groups of land users by generating information about the economic and ecological effects of particular decisions [32]. Pacini et al. applied a holistically designed ecological–economic model to different policy scenarios [33]. Estes et al. designed a model to explore the potential for targeting agricultural expansion in ways that achieve quantitatively optimal trade-offs between competing economic and environmental objectives to find potential compromises [34]. Coleman et al. adopted a model framework that simulates spatial and temporal interactions in agricultural landscapes and can explore trade-offs between production and the environment [35]. Ditzler et al. coupled a bio-economical farm model, evaluating the productive, economic, and environmental farm performance, with a multi-objective optimisation algorithm that generates a large set of Pareto-optimal alternative farm configurations [36].

The analysis of the previous literature highlighted the need to quantify the emission abatement costs at the local and farm scales since most of the studies dealt with aggregate estimations. To fill this gap, this study used a tool previously designed to assess sustainability in organic and conventional farming with a multi-criteria approach [37]. The tool has been further developed to estimate economic and environmental performance at the farm level, using real farm data in specific contexts. This approach allowed for analysing both farm-level decisions and policy scenarios. To the best of our knowledge, this approach has not been adopted in any other similar studies.

The paper is organised as follows. Section 2 explains the data used and provides essential information on the research strategy and the model. Section 3 presents the results of the analysis. Finally, a discussion and conclusions are drawn in Section 4.

2. Materials and Methods

2.1. Data: The RICA Database

This analysis method has been tailored around the RICA database, the Italian section of FADN, one of the major EU-wide data sets and a fundamental information tool used in the decisional processes dealing with the design of the EU Common Agricultural Policy. FADN collects accountancy information from a representative sample of EU farms. In Italy, data collection and maintenance are carried out by CREA-MIPAAF (National Council for Agriculture Research and Agricultural Economics of the Ministry of Agricultural, Food and Forest Policies). The collected information is structural (e.g., cropped surface, workforce, etc.) and economical (e.g., producing value, goods and services purchased and sold, subsidies, etc.).

In 2003, the principle that the farm sample should represent a country farm universe was introduced, and farm selection has been in agreement with the results of the investigation of economic performances of farm holdings (REA) managed by the Italian National Institute for Statistics (Istat). Such innovation allows for obtaining an integrated survey structured unit that is able to considerably increase record reliability. Such a methodology has also allowed, since 2003, to give each farm a weight, estimating its representation on a national basis, which is obtained from three data: location (NUTS2), economic size (since 2009, expressed in euros), and type of farming (following the Neyman methodology) [38].

Even though CREA preliminarily checks data, they require further verification to detect and correct anomalies of values (e.g., numbers including characters) and labels (e.g., non-uniform ASCII coding). Successively, a filtering procedure was applied, aiming to restrict the farm universe. In fact, for this study, a preselection of farms was performed, and we retained only farms with arable land-use located in flat and steep areas (Figure 1).

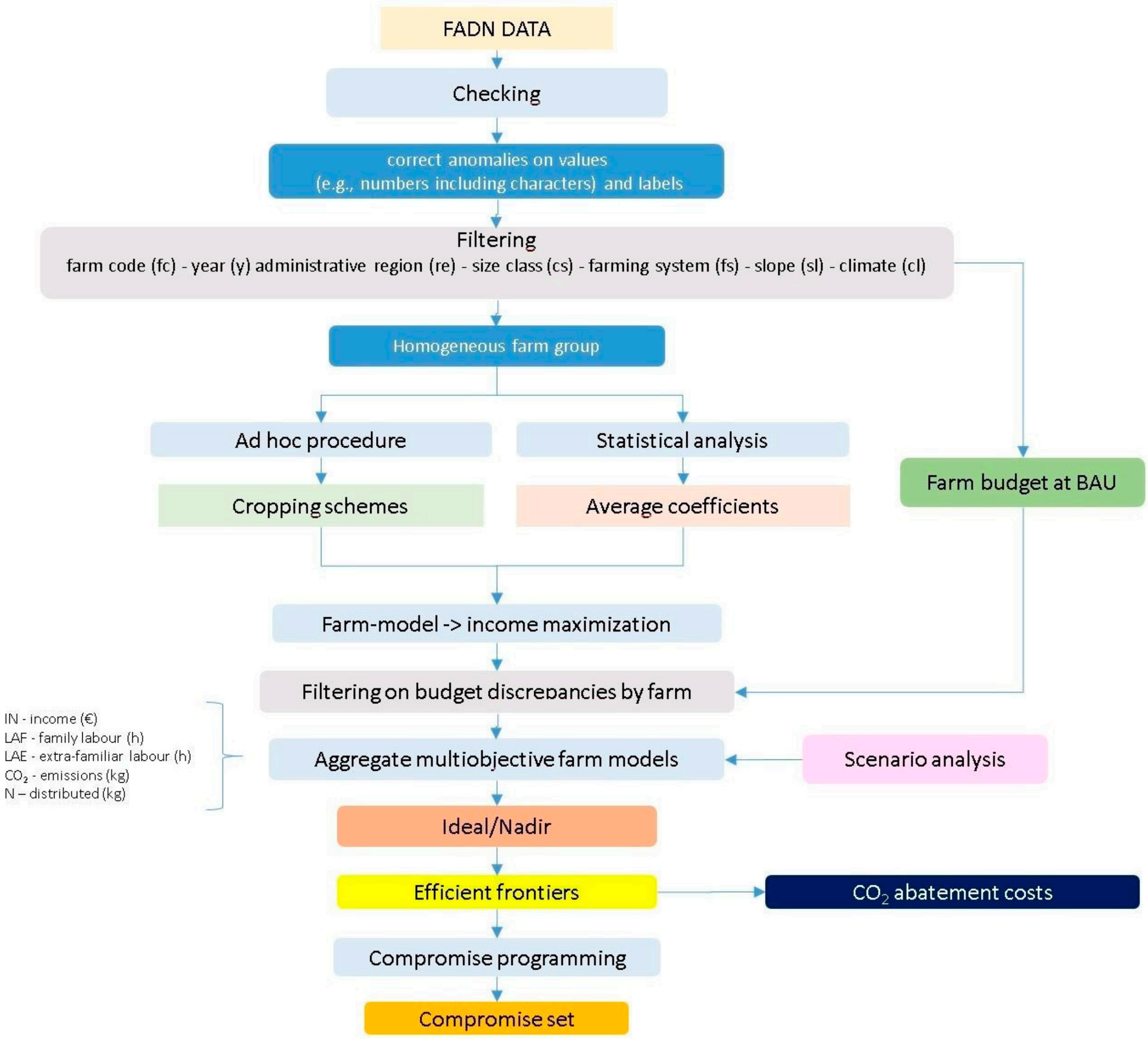

Figure 1. The flow chart of the methodology.

Data from the RICA database were used for the following specific purposes:

- to obtain technical parameters for the model;
- to extrapolate the cropping schemes;
- to select farms for simulations;
- to validate the results.

A schematic representation of the procedure is presented in Figure 1.

2.2. Multi-objective Analysis

Available RICA data supported the identification of different criteria and the related indicators: income (IN—€), family labour (LAF—h), external labour (LAE—h), emissions

(CO_2—kg), distributed nitrogen fertilisers (N—kg). All the criteria were to be minimised, except income.

When more conflicting criteria are simultaneously considered, no optimal solution exists since one criterion may improve only by worsening others.

The RICA dataset allows for describing each criterion as a function of production processes at the farm level. A process describes how a specific crop is cultivated, considering input and output both in quantity and economic terms. Therefore, the multi-objectives approach could be adopted.

The LMP, also known as vectorial optimisation, is based on linear functions and preserves the optimisation approach, characterising basic linear programming. The method is suitable when all alternatives can be identified, and the objectives are functions to be minimised or maximised. In this case, the problem was reduced to the identification of the set of feasible, non-dominated solutions, as in Equation (1):

$$\text{Eff } f(x) = [f_1(x) \ldots f_j(x) \ldots f_m(x)] \tag{1}$$

where Eff is the efficient solution set and represents the Pareto or efficient frontier, fj is the objective function of criterion j ∈ [1:m], and x is a decision variable array. Solutions are constrained by available resources and technologies and any other relevant aspect of the problem. The problem has a representation in the alternatives' space (X), showing which production process should be activated, and a complementary representation in the objective space $f_j(x)$, quantifying the effects for all the criteria by the selected indicators.

Solutions are found in a common approach, maximising a variable Z, which is the weighted sum of the normalised objectives (Equation (2)):

$$Z = \sum_j w_j \cdot |f_j - f^*| \,/\, |f_{max} - f_{min}| \tag{2}$$

where Z is the objective value, representing the aggregated weighted value of the normalised criteria, and $w_j \in [0:1]$ is the weight of indicator f_j, and the sum of all the w_j has a value of 1. It should be clarified that w_j is a technical coefficient quantifying the relative importance of criteria. Since Z is a linear combination of the objective values, it requires that the selected criteria are independent.

This optimisation approach was based only on technical information derived from RICA, and decision-makers' preferences were not requested. Normalisation was needed since the criteria were measured in different scales and units. In Equation (2), f* represents the minimum or the maximum, depending on whether the criterion has to be maximised or minimised. In all cases, normalised values of 0 correspond to the worst case, and 1 to the best case. In the first stage, estimations of maximum and minimum for each criterion were performed, which implied solving a number of problems equal to the number of criteria under the same constraints.

As weight values affect results, different weight combinations can be adopted to explore the feasible space. When two solutions are compared, it is possible to identify the conflict between the criteria to move from one solution to another and the existing trade-off. When one of the criteria is expressed in monetary terms, the trade-off represents the cost implied by the other criterion's optimisation. In our case, reducing CO_2 emissions (criterion 1) corresponded to decreasing income (criterion 2), and the monetary loss suffered by the farmer was the estimated CO_2 reduction cost.

A parametric analysis of the weights allows for estimating efficient frontiers. The existing variability in the alternatives space affects the number of feasible solutions, which is not necessarily equal to the number of weighted combinations since more combinations can generate the same solution.

2.3. The Tool: MAD 2.0

MAD 2.0 is a multi-farm model based on mathematical programming techniques and designed to work with the RICA database. The model was written and solved in GAMS (General Algebraic Modelling System) software [39].

The model assumes that a farm may have only one regime—conventional or organic; splitting or transient conditions are not considered. Technical coefficients, including resource use, production and related costs and revenues, are estimated annually from the RICA database. In the short time horizon, new investments are not considered, and every component that is not related directly to arable land is assumed to be constant.

Seven indices identify each farm:

- farm code (fc), which identifies the farm in the RICA database;
- year (y), relevant because of climate trends and price variations over time—available years are 2008–2018;
- administrative region (re), as defined by RICA, represents a relevant aggregate level for analysis;
- land size class (cs), considering only the arable surface, defined by the limiting values: 5, 15 and 40 ha (RICA); such classes create more homogeneous groups of farms within the total sample;
- farming system (fs): conventional (c) or organic (o);
- slope (sl), a class of slope following RICA, assigned to the farm on the basis of the prevalence of that of arable surfaces: G1—flat (slope 0%), G2—mild (0% < slope < 10%), G3—steep (slope > 10%);
- climate (cl), a piece of information missing in RICA; classification has been done using a national phyto-climatic mapping developed by Tomasselli [40] and Pedrotti [41], defining five classes: Z1—Lauretum, Z2—Quercetum, Z3—Castanetum, Z4—Fagetum and Z5—Picetum; the choice revealed to be a good compromise in terms of resolution and complexity. The climate map has been used to assign a climate class to each municipality by a prevalence criterion, then further assigned to the farmer.

Each combination of the previous indices identifies a "context" in equations, represented as "az".

2.3.1. Cropping Schemes

Land use is articulated in crops (cc), which are split into arable (cr) and permanent crops (e.g., pastures). As only the first ones are responsive to short time farm decisions, arable land-related activities are the only ones optimised by the model. However, to compare model accounting estimates with the standard RICA budget, all the other activities were included in the analysis but kept fixed to the observed farm values.

A novel approach, able to obtain flexibility and representativeness of the farm territorial context, was adopted to model land use and the associated production techniques. It was based on the introduction of "cropping schemes" (sc), that is, land-use combinations characterising a certain context. A cropping scheme is defined based on observed data considering both crops and crop groups. A group includes crops similar in terms of agronomic aspects and technique in a certain context and requires similar equipment at a farm scale. Observed groups included cereal, industrial, and horticultural crops. Elements of the groups were only the crops observed in the RICA data by context, which implies that the same group could include different crops by region, climatic zone, and farm class [42]. The model assumes that a farm can grow any crops of the same group in the given cropping scheme. A cropping scheme, by construction, includes actual land use, while crop substitution within a group entails flexibility while preserving the current type of farming.

In the first phase, statistical analysis quantified the observed surface by context. In a second phase, shifts from such values were calculated, quantifying the minimum and maximum crop size by crop and group based on the available information on farmer behaviour and the market.

Three constraints were therefore adopted:

$$sa_{az} = \sum\nolimits_{cr\,|\,sc} S_{az,cr} \quad (3)$$

$$sa_{az} = \sum\nolimits_{gr\,|\,sc} SG_{az,gr} \quad (4)$$

$$ST_{cr} = \sum\nolimits_{az} S_{az,cr} \quad (5)$$

Equation (3) imposes that land allocation (S) based on available cropping schemes (sc) reproduces the current arable surface (sa) at a farm level (az), allowing for crop substitution within a group within the limits of the cropping schemes.

Equation (4) quantifies the surface by group (SG) at the farm level.

Equation (5) is a territorial constraint that quantifies the aggregate surface by crop at a territorial level (ST).

The variables S, SG and ST have boundaries that limit land-use allocation at a farm level; the first two being based on current land use, and the latter on markets.

2.3.2. Production Factors and Resource Usage

The crop data include information on different production factors, among which labour (LA), articulated by labour provided by the farmers' family (LAF), external labour (LAE), and machinery use with a farmer component and an external one represented by a third party's services are particularly relevant.

Constraints related to labour are calculated over all crops, and not only the arable ones; Equation (6) introduces the labour balance between the components, and Equation (7) quantifies the labour requirement at a farm scale from a crop scale:

$$LA_{az} = LF_{az} + LE_{az} \quad (6)$$

$$LA_{az} = \sum\nolimits_{az,cc} la_{cc} \cdot S_{az,cc} \quad (7)$$

where 'la' represents the labour requirement of a given crop (cc) and S represents the crop surface.

As mentioned above, machinery use is assumed to be the major source of emissions (CO_2). Emissions can be calculated from the working time multiplied by a coefficient quantifying an average engine fuel hourly consumption (CO_2). RICA provides information on the time spent by farm machinery by crop (tm), but only the cost of third party services (se); in the latter case, time employed can be estimated by dividing the cost by an hourly tariff (tt), as shown in Equation (8):

$$CO2_{az} = \sum\nolimits_{cc} S_{az,cc} \cdot [tm_{cc} + se_{cc}\ /tt] \cdot co2 \quad (8)$$

Distributed nitrogen fertiliser (N) is quantified considering the sum by crop (cc) of the amount distributed per surface unit (nf), multiplied by the surface (S), as in Equation (9):

$$N_{az} = \sum\nolimits_{cc} S_{az,cc} \cdot nf_{cc} \quad (9)$$

2.3.3. The Economic Component

Because the model is focused on the short term, farm income (IN, Equation (10)) is a gross value given by the value of products sold, plus subsidies (SU, Equation (11)), minus the total variable costs (VC, Equation (12)). The model follows the RICA classification of outputs into raw, transformed, and by-products, assuming that they could all be sold. Therefore, the first component in Equation (10) equals the sum by crops (cc) and products (pp) of unitary yields (q) and price (p), multiplied by the cultivated surface (S):

$$IN_{az} = \sum\nolimits_{cc\,|\,az} [S_{cc} \cdot \sum\nolimits_{pp\,|\,cc} q_{pp} \cdot p_{pp}] + SU_{az} - VC_{az} \quad (10)$$

Subsidies (SU, Equation (11)) have been considered when related to the first pillar, as regulated by EU Reg. 2013/1307 [43], including decoupled support (SD) and coupled aids (sa) for specific crops, including durum wheat, protein crops, oil/protein crops, soybean, sugar beet and field tomato:

$$SU_{az} = SD_{az} + \sum\nolimits_{cc \mid ss} [S_{az,cc} \cdot sa_{cc}] \tag{11}$$

Costs (co) per surface unit are those related to resources (rr) used, including the previous year's costs (fall seeding), energy, external services, seeds, pesticides, fertilisers, water, transformation, marketing, insurances, certification, and other costs. The total amount of variable costs (VC) is given by Equation (12):

$$VC_{az,} = \sum\nolimits_{cc} [S_{az,cc} \cdot \sum\nolimits_{rr} co_{cc,rr}] \tag{12}$$

2.3.4. Objective Function

The model identifies the best combination of crops on the available arable surface area, maximising the variable Z given by the objective function Equation (13):

$$Z = \sum\nolimits_{az} u_{az} \cdot \sum\nolimits_{j} w_j \, I_{j,az} \tag{13}$$

where $I_{\{1,2\}} = \{IN, CO_2\}$ are the normalised values of the criteria, u_{az} is the factor accounting for farm representativeness at a country level (SAMPLE table in RICA), and w_j are the objective weights, as in Equation (2).

The model has been used to perform a frontier analysis for the contexts described above. The frontier derivatives allow for evaluating the abatement costs of CO_2 (AC): Δ IN/Δ CO_2.

The goal was to identify the likelihoods and differences in emissions and ACs amongst contexts due to different local conditions deriving from climate, technological, and cultural aspects.

2.3.5. Coefficients and Algorithms

Statistical algorithms were implemented using the R software package [44]. Specific code was developed to identify and remove outliers and derive the average technical coefficients by crop, product (quantity and prices), and subsidies. Averages and variations were estimated for every quantitative observation included in RICA.

For the same crop, the technical coefficients derived from the RICA data describe a process for a given context (region, climate, slope, regime) and have a general value beyond the current analysis.

Farm surface area classes (sa) were merged to guarantee adequate sample numerosity. In classes with a small size or large variability, the technical coefficients were not estimated. This case occurred for groups defined by terms used occasionally or that were strongly crop-dependent. Coefficients such as previous year costs, insurances, certification were available only for a few crops.

Coefficient availability also affected the selection of crops for successive analysis, as farm filtering, based on the comparison between estimated and observed accountancy items, was applied.

3. Results

The model has been validated by comparing model estimates with the RICA budget at the farm level, representing the Business as Usual (BAU) scenario. Only farms with a difference in total cost and product sold lower than 20% in both values were considered. This selection further reduced the sample numerosity but highly increased representativeness.

Parametric analysis on weights was conducted, moving from $w_{IN} = 1$, $w_{CO2} = 0$ to $w_{IN} = 0$, $w_{CO2} = 1$, considering a 5% variation and requiring 21 steps, for all the Regions and different years. Since farmers were assumed to be income maximisers, the former combination represents the existing situation, while all the other combinations identify efficient solutions with lower incomes and CO_2 emissions levels. Due to the conflict between the selected criteria, a reduction in the growth in emissions, which is desirable from an environmental perspective, can be obtained only by lowering the income.

Only contexts with at least five farms were considered for this study; the analysis includes, in total, 65 contexts in 10 regions in the north, centre and south of Italy, representing over 10,000 farms and covering about 230,000 hectares. The results by context are reported in Appendix A. The first column identifies the context; columns 2–4 quantify the number of farms, land surface area and the number of crops observed in the context; columns 5–9 include five indicators: INC, CO_2, N, LAF, and LAE; columns 10–15 the variation of the indicator with respect to the BAU; column 16 reports the average abatement cost for a kilogram of CO_2 (AC).

Context distribution among regions and classes of land size (Table 1) show that contexts in cs1, (arable land < 5 ha) are only in four out of five regions (LOM, ERO, ABR, LAZ; CAL) and have only middle-size farms, while in the other regions, the three larger classes are always present. Most farms are located in flat (G1) and mild slope (G2) areas, while only six are in steep slope areas (G3).

Table 1. Number of contexts by region, climatic area, and classes of land size.

	Land Size Class				Slope	Land Size				Slope	Land Size Class			Slope	
Region and Climate	**cs1**	**cs2**	**cs3**	**cs4**	**G1**	**cs1**	**cs2**	**cs3**	**cs4**	**G2**	**cs2**	**cs3**	**cs4**	**G3**	**Total**
LOM		**2**	**2**	**2**	**6**	**1**	**1**	**1**		**3**					**9**
Z3		1	1	1	3	1	1	1		3					6
Z4		1	1	1	3										3
VEN		**1**	**1**	**1**	**3**										**3**
Z3		1	1	1	3										3
ERO	**1**	**1**	**1**	**1**	**4**			**1**	**1**	**2**			**1**	**1**	**7**
Z3	1	1	1	1	4			1	1	2			1	1	7
MAR			**1**		**1**			**1**	**1**	**2**	**1**	**1**	**1**	**3**	**6**
Z3			1		1			1	1	2	1	1	1	3	6
TOS		**2**	**1**	**1**	**4**			**2**	**2**	**4**		**1**	**1**	**2**	**10**
Z1		1	1	1	3			1	1	2					5
Z3		1			1			1	1	2		1	1	2	5
ABR		**1**	**1**		**2**	**1**	**2**	**1**	**1**	**5**					**7**
Z1			1		1		1			1					2
Z3		1			1	1	1	1	1	4					5
LAZ	**1**		**1**	**1**	**3**			**1**	**1**	**2**					**5**
Z1			1	1	2										2
Z2	1				1										1
Z3								1	1	2					2
CAM		**2**	**2**		**4**		**1**	**1**	**1**	**3**					**7**
Z1			1		1				1	1					2
Z2		1			1										1
Z3		1	1		2		1	1		2					4
PUG		**2**	**3**	**2**	**7**		**1**		**1**	**2**					**9**
Z1		1	1	1	3										3
Z2		1	1		2										2
Z3			1	1	2		1		1	2					4
CAL							**1**	**1**		**2**					**2**
Z1							1	1		2					2
Total	**2**	**11**	**13**	**8**	**34**	**2**	**6**	**9**	**8**	**25**	**1**	**2**	**3**	**6**	**65**

Regions: LOM = Lombardia, VEN = Veneto, ERO = Emilia-Romagna, MAR = Marche, TOS = Toscana, UMB = Umbria, LAZ = Lazio, CAM = Campania, PUG = Puglia, CAL = Calabria; Climates: Z1 = Lauretum, Z2 = Quercetum, Z3 = Castanetum, Z4 = Fagetum; G1 = flat, G2 = mild slope, G3 = steep slope; arable land size: cs1 = <5 ha, cs2 = 5−15 ha, cs3 = 15−40 ha, cs4 = >40 ha

The total land surface area is over 1.2 million hectares, nearly 50% of which is represented by large farms. Only 4390 hectares are in small farms, while the rest of the area is allocated to the central classes. Most of the area is in the north of Italy, and ERO is the most represented region (Table 2).

Table 2. Total surface by region and classes of arable land size.

Region	cs1	cs2	cs3	cs4	Total by Region
LOM	168	46,256	91,465	161,388	299,277
VEN		52,279	48,723	53,313	154,315
ERO	2406	42,588	116,252	244,603	405,849
MAR		1250	27,198	23,973	52,421
TOS		4433	14,996	48,073	67,502
ABR	763	6448	5899	1740	14,850
LAZ	1053		28,215	34,187	63,455
CAM		8773	13,002	1261	23,036
PUG		20,049	67,004	53,420	140,473
CAL		2538	7413		9951
Total by cs	4390	184,614	420,167	621,958	1231,129

Regions: LOM = Lombardia, VEN = Veneto, ERO = Emilia-Romagna, MAR = Marche, TOS = Toscana, UMB = Umbria, LAZ = Lazio, CAM = Campania, PUG = Puglia, CAL = Calabria; arable land size: cs1 = <5 ha, cs2 = 5–15 ha, cs3 = 15–40 ha, cs4 = >40 ha.

The context PUGcs2G1Z2 (PUG = Puglia, cs2 = 5–15 ha, G1 = flat, Z2 = Quercetum) is described in detail, as an example of the methodology.

Table 3 shows the values of the indicators; the resulting values are illustrated in Figure 2. Only five points are reported since more weight combinations gave identical results. The chart has iteration along the horizontal axis and the income measured in euros down the left vertical axis; the other four criteria are on the right vertical axis. All values refer to one hectare of land. The BAU point on the extreme left of the horizontal axis corresponds to iteration 1; moving from p1 to p2, income decreases by EUR 33.27 and CO_2 reduces by 25.71 kg, which gives an AC of 1.29 EUR/kg. Comparing p3 with p1, the variation becomes 86.75 and 5.98, giving an AC of 14.56 EUR/kg. At p4, the AC rises to 15.68 due to an income loss of 253.77 and a reduction of 16.18 kg of CO_2. The next line, p5, shows a reduction in income of EUR 640.08, while CO_2 reduction lowers to 25.59 kg, and AC jumps to 25.01 EUR/kg.

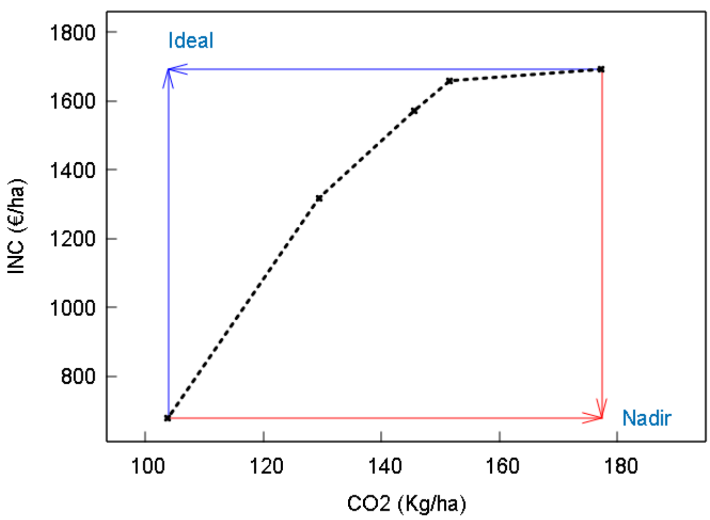

Figure 2. Efficient frontier INC/CO_2 in the context of PUGcs2G1Z2, 2016. INC = income, CO_2 = carbon dioxide emissions.

Table 3. Indicators' values at different efficient levels of INC/CO_2 in PUGcs2G1Z2 (PUG = Puglia, cs2 = 5–15 ha, G1 = flat, Z2 = Quercetum).

p	INC	CO_2	N	LAF	LAE	D.INC	D.CO_2	AC
1	1692.10	177.33	76.18	91.86	17.86			
2	1658.83	151.62	71.41	84.76	17.65	33.27	25.71	1.29
3	1572.08	145.66	60.79	82.98	17.65	86.75	5.96	14.56
4	1318.31	129.48	53.39	97.30	15.22	253.77	16.18	15.68
5	678.23	103.89	52.73	29.84	14.45	640.08	25.59	25.01

p = switch point, INC = income, CO_2= carbon dioxide, N = nitrogen, LAF = family labour, LAE = external labour, D.INC = delta income, D.CO_2 = delta greenhouse gases, AC= abatement cost.

The relation between income and emissions can be well represented by a chart showing the efficient frontier (Figure 2) with income measured in euros along the vertical axis and CO_2 emissions along the horizontal axis. Since farmers are income maximisers, the highest income value identifies the current BAU situation, which is the extreme upper right in the frontier; such a point corresponds to the highest emission levels. Points along the frontier represent feasible solutions characterised by lower income levels and lower emissions.

As far as the other criteria are concerned, Table 3 and Figure 3 show the complete picture. At the switch point 2, the use of N decreased from 76.18 kg/ha to 71.41 kg/ha −4.77%; the impact on employment was also negative: family labour (LAF) moved from 91.86 h/ha to 84.76 h/ha −7.1%, while external labour (LAE), which requires 17.86 hours at BAU decreased to 17.65 −0.21%. In this context, all the indicators decreased with CO_2 reduction, but family labour, at point 4, had an opposite trend, rising by +14.32%, probably due to substitution with mechanical operations requested to comply with the environmental goal.

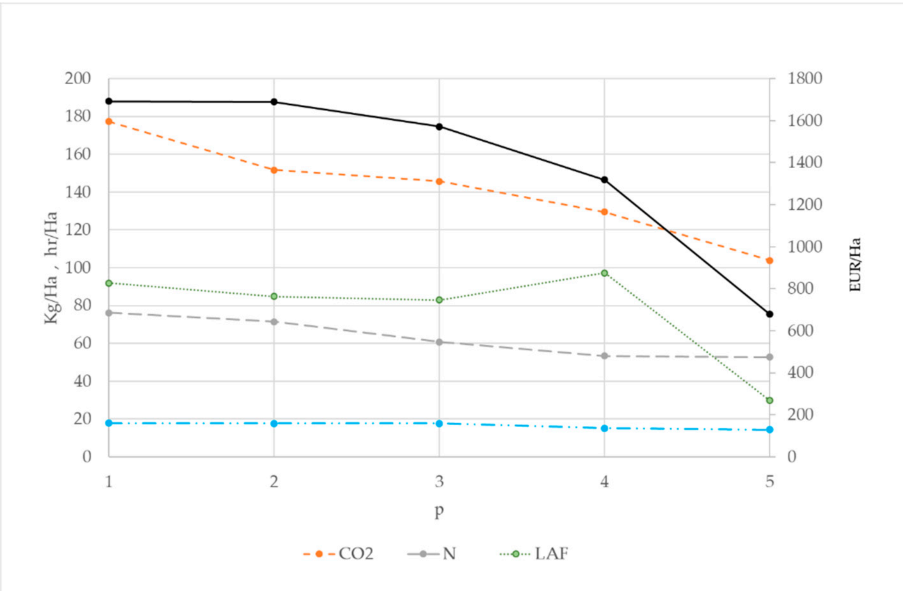

Figure 3. The impact of CO_2 emission reductions on selected criteria in PUGcs2G1Z2 2016. *p* = switch point, INC = income, CO_2 = carbon dioxide emissions, N = nitrogen distributed, LAF = family labour, LAE = external labour.

The previous charts describe the results in the objective space; a corresponding figure can be obtained in the criteria space, where production processes are described. Figure 4 shows the distribution of crops for the previous context, only crops that cover more than 3% of the total surface were included. Iterations are along the horizontal axis and the total surface in hectares is along the vertical axis. Durum wheat, the main cultivation currently observed (iter 1), at point 2 decreased less than 2%, then lost surface, dropping from over

4400 ha to 3600 ha (−18.58%), then keeps stable at around 3700 ha. Most profitable crops, including fennel and melon, decreased the covered surface substantially, by more than −80%. An opposite trend showed sunflowers rising from 177 to 270 ha + 52%, and unaided set-aside land rising from 177 ha to 227 hectares (+28%). Broad beans kept stable, while industrial tomatoes kept stable until point 3, then lost around 10%, and were substituted by table tomatoes requiring more labour and fewer mechanical practices. Other labour-intensive crops entered the rotation but with a very limited surface, while the highly mechanised crops disappeared. An extensification and diversification process was adopted to reduce the CO_2 emissions in the short term.

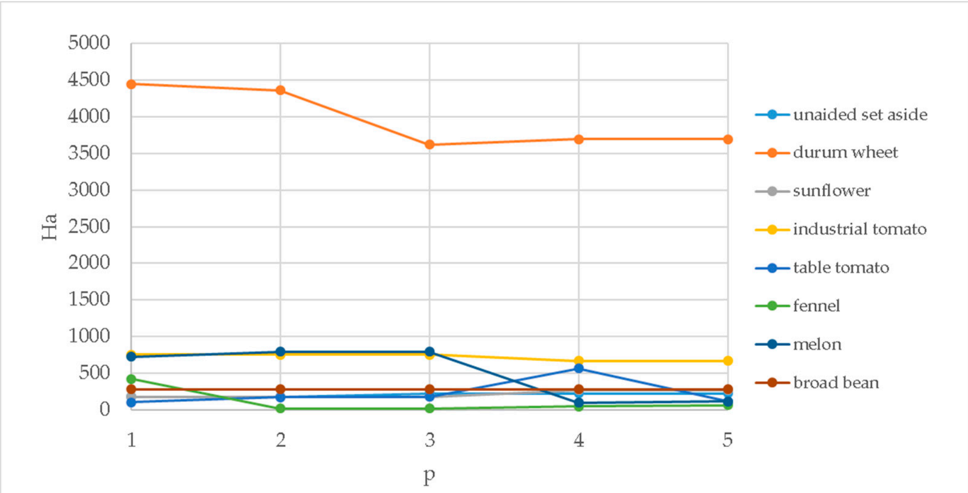

Figure 4. The impact of CO_2 emission reductions on land use in PUGcs2G1Z2, 2016. *p* = switch point.

The analysis can be repeated for all the observed contexts, but for the sake of brevity, we present a comparative analysis considering all 10 regions, and all the contexts provided useful insight on the income/CO_2 emissions relationship.

Table 4 presents the minimum abatement cost for a kilogram of CO_2 by regions and slope. Only ACs lower than EUR 1 were included. Regions are along the rows; in the PUG case, more rows identify increasing levels of reduction. LAZ has no value due to ACs higher than the entry level.

Table 4. Minimum abatement cost for a kilogram of CO_2 by region and slope.

Region	G1	G2	G3
LOM	0.537	0.555	
VEN	0.102		
ERO	0.109		
MAR	0.913	0.070	
TOS	0.056	0.250	0.786
ABR	0.268	0.612	
CAM	0.482	0.607	
PUG (p1)	0.364	0.159	
PUG (p2)	0.487		
PUG (p3)	0.835		
CAL		0.576	

Regions: LOM = Lombardia, VEN = Veneto, ERO = Emilia-Romagna, MAR = Marche, TOS = Toscana, UMB = Umbria, CAM = Campania, PUG = Puglia, CAL = Calabria; G1 = flat, G2 = mild slope, G3 = steep slope; p1, p2, p3 = switch points.

A clear relation seems to exist between the AC and slope; G1 shows lower values in all regions except PUG and MAR, where the highest value 0.913 EUR/kg was observed.

The best performance with the lowest AC is in TOS, with the lowest observed AC, equal to 0.056 EUR/kg (Table 4).

Farm size seems to be linked to the capacity to reduce emissions (Table 5). cs1 has a higher AC; this is probably due to the higher efficiency of larger farms in technical operations.

Table 5. Minimum abatement cost per kilogram of CO_2 by arable land size class.

Arable Land Size Class	Min ABATEMENT COST
cs1	0.862
cs2	0.056
cs3	0.070
cs4	0.109

Arable land size classes: cs1 = <5 ha, cs2 = 5–15 ha, cs3 = 15–40 ha, cs4 = >40 ha.

We illustrate our findings for four cases with conventional management (c) and plain terrain (G1) data, including Lombardy (LOM) and Emilia-Romagna (ERO) for the north, Tuscany (TOS) for the centre, and Puglia (PUG) for the south of Italy, with climate corresponding to Z3 for LOM and ERO, Z1 for TOS, and Z2 for PUG.

Figure 5 shows the efficient frontiers, with income along the vertical axis and emissions along the horizontal axis. Colours identify the farm size classes (cs1–cs4); not all the classes were always present since the interval chosen covered only a part of the feasible space, and in some cases, the first class fell out. All values refer to one hectare of land. Cross-squared symbols represent the ideal values, identifying infeasible solutions where both criteria are at the optimum; such points are referenced to identify the compromise range on the frontier, characterised by the Euler and Chebyshev distances from the previous analysis [30].

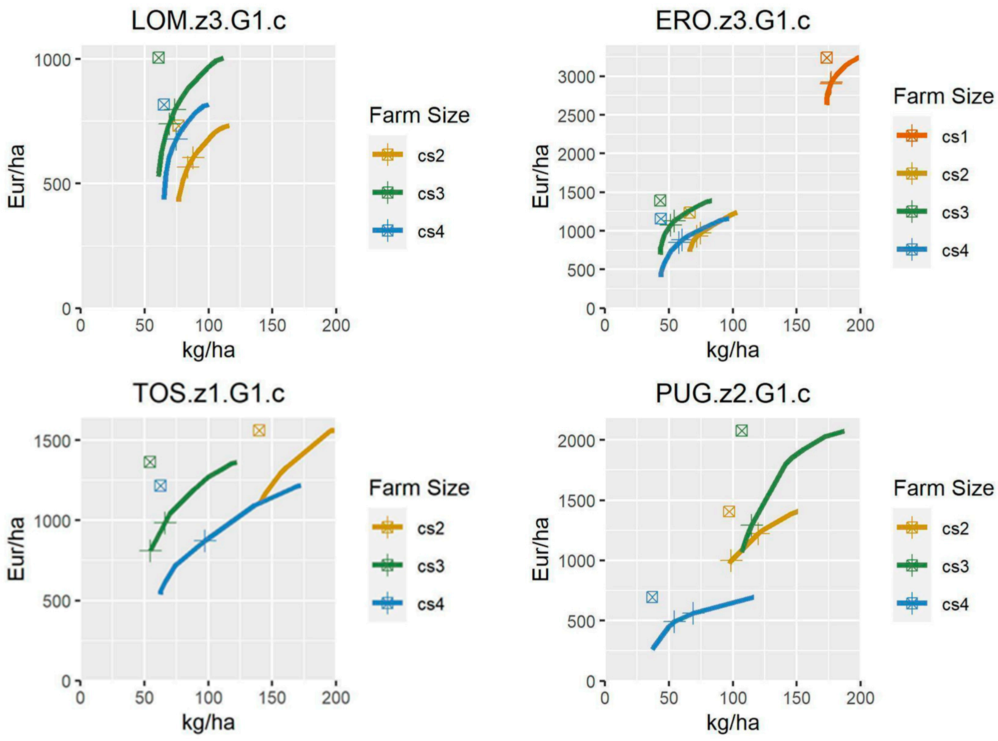

Figure 5. Income/CO_2 emissions frontiers by regions and arable land size class. Regions: LOM = Lombardia, ERO = Emilia-Romagna, TOS = Toscana, PUG = Puglia; climates: Z1 = Lauretum, Z2 = Quercetum, Z3 = Castanetum; G1 = plain, G2 = mild slope, G3 = hilly; farming system: c = conventional, o = organic; arable land size classes: cs1 = <5 ha, cs2 = 5–15 ha, cs3 = 15–40 ha, cs4 = >40 ha.

The frontiers have similar shapes but a very different range of values. Within a region, differences emerged among classes and greater ones among regions.

Current income levels are quite different, ranging from about 3500 EUR/ha in ERO cs1 to about 750 EUR/ha in LOM cs2 and PU cs4. Emissions show a more limited range of values among observed situations, ranging from nearly 200 kg/ha to less than 100 kg/ha.

In general, CO_2 emissions per hectare were lower in larger farms (classes cs3, cs4), which can depend on higher efficiency in the use of machinery but also, and more probably, from more extensive cultivation in comparison to smaller farms (cs1, cs2), where higher emissions follow higher incomes.

Figure 6 shows the marginal abatement cost (MAC) calculated as the variation of the two following points of the frontier. In this case, all the charts have equal values on the axes.

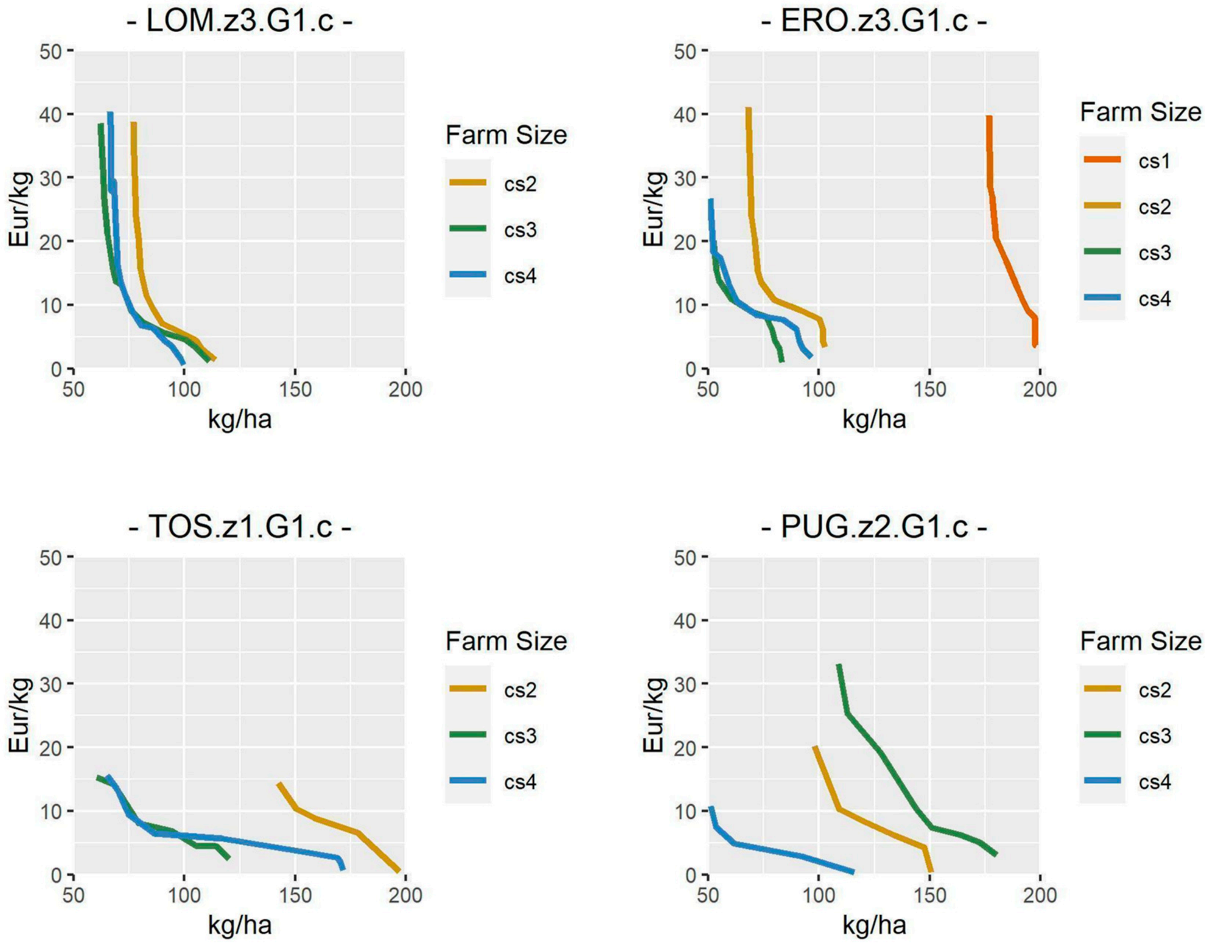

Figure 6. Variations of the abatement costs at different CO_2 emission levels by region and arable land size class. Regions: LOM = Lombardia, ERO = Emilia-Romagna, TOS = Toscana, PUG = Puglia; climates: Z1 = Lauretum, Z2 = Quercetum, Z3 = Castanetum; G1 = plain, G2 = mild slope, G3 = hilly; farming system: c = conventional, o = organic; arable land size classes: cs1 = <5 ha, cs2 = 5–15 ha, cs3 = 15–40 ha, cs4 = >40 ha.

Almost every curve shows S-shaped behaviour. Moving from BAU, abatement costs grow rapidly, and then reach a nearly stable value due to the existence of alternatives that preserve income. A further reduction in emissions corresponds to a dramatic MAC increase, particularly in the north.

Finally, the study shows that a reduction of CO_2 emissions higher than 5 kg/ha, at an AC lower than 1 EUR/kg is affordable only in six s regions, among which ABR, and LOM show higher potential (Table 6).

Table 6. Contexts with CO_2 emissions higher than 5 kg/ha at an AC lower than 1 EUR/kg.

Context	INC	D.CO2	Abatement Cost
	Euro	**kg**	**Euros/kg**
ABRcs2G2Z1	782	−128.91	0.612
LOMcs4G1Z4	56	−31.25	0.537
CAMcs2G1Z3	1640	−11.40	0.482
LOMcs3G2Z3	548	−9.58	0.555
TOScs4G3Z3	82	−6.79	0.786
ABRcs3G1Z1	833	−5.70	0.530

INC = income, $D.CO_2$ = delta CO_2 emissions level; regions: ABR = Abruzzo, LOM = Lombardia, CAM = Campania, TOS = Toscana; arable land size classes: cs1 = <5 ha, cs2 = 5–15 ha, cs3 = 15–40 ha, cs4 = >40 ha; G1 = plain, G2 = mild slope, G3 = steep slope; climates: Z1 = Lauretum, Z2 = Quercetum, Z3 = Castanetum, Z4 = Fagetum.

4. Discussion and Conclusions

The assessment of economic and environmental sustainability of agricultural systems represents a critical issue, which has been addressed in this work with an integrated approach based on the LMP to explore the abatement costs of CO_2 for a set of representative contexts of Italian arable land agriculture.

The study has shown a quite diversified situation regarding income and emission levels per hectare across Italian regions and farm classes, due to diversified cropping systems and production processes. A more homogeneous situation emerged, considering the marginal abatement cost, which spanned 0–40 EUR/kg of CO_2, but below EUR 1, emissions showed nearly no reduction.

ETS, introduced by EU policies to reduce industrial emissions, got a price raise in the last 10 years from 0.10 to 0.23 EUR/kg of CO_2, and further increases are expected that could further increase the price to 0.4 EUR/kg of CO_2.

Comparing ETS values to MACs in the agricultural systems taken into account highlighted a difference of 1 order of magnitude, which can probably be ascribed to the huge difference in efficiency between the industrial and agricultural production systems. Only in a few cases could relevant emission reductions be obtained at a cost lower than 1 EUR/kg. Therefore, to reduce emissions, innovation should be introduced in the arable cropping systems in terms of technologies with a lower use of resources, especially internal combustion engine machinery, and a general increase of energy efficiency.

The simulation and optimisation tool developed proved to produce insightful responses to estimated CO_2 emissions and their abatement costs. It is important to highlight that this analysis was based on a short-term perspective. Therefore, it is useful to provide foresight on possible immediate impacts and contingency adjustments implemented by farmers in response to environmental policies to reduce emissions [45–47]. However, further research is necessary to complement this analysis and provide a medium to long-term perspective, in which structural adaptation on the supply side, such as land-use changes, technological innovation, intensification or extensification [48,49], supply chain adaptations, and market developments on the demand side, [50,51] are also allowed.

The FADN-compliant Italian RICA has been shown to collect information adequate to perform quantitative analysis of economical and agrotechnical aspects.

Data availability is at the base of statistical approaches adopted to derive technical parameters. An important contribution of this analysis lies in its reliance on actual farm accountancy data rather than simulation-based data. Such context-dependent parameters, describing production processes at a crop level, can be useful to other bio-economic models.

The model developed, designed to use RICA's information solely and based on an innovative concept of a cropping scheme to simulate land-use adaptation, proved reliable and capable of conducting multi-criteria analysis.

Nonetheless, both the model and its background database can be improved. The model is ready to host more equations and constraints to study other farm contexts and consider other socio-economic and environmental criteria.

Several aspects can be enhanced in the RICA database to collect records that consistently refer to the same farm over the years, link to other databases, and enrich the information on non-conventional agricultural approaches (e.g., organic).

Further research may be addressed to update the analysis to more recent RICA surveys and introduce stakeholder perspectives. Collaborations with the RICA maintenance team and other national and international research and survey institutions could open further opportunities to develop the tool.

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Data Availability Statement: Restrictions apply to the availability of these data. The data were obtained from the Council for Agricultural Research and Economics (CREA) and are accessible at the URL https://bancadatirica.crea.gov.it/Account/Login.aspx with the permission of CREA.

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Appendix A

CONTEXT	*FARM*	*SURF*	*CC*	*INC*	*CO_2*	*N*	*LAF*	*LAE*	*D.INC*	*D.CO_2*	*D.N*	*D.LAF*	*D.LAE*	*AC*	*cs*
LOMcs1G2Z3	67	168	6	921	294	32	82.6	0							cs1
LOMcs1G2Z3	67	168	6	894	289	23	79.3	0	−27.4	−5.65	−9.02	−3.3	0	4.85	cs1
LOMcs2G1Z3	7814	39070	28	714	120	135	55.8	0							cs2
LOMcs2G1cZ3	7814	39070	28	710	117	133	54.8	0	−3.7	−2.29	−2.05	−0.92	0	1.616	cs2
LOMcs2G1Z4	101	503	12	2691	120	43	45.4	0							cs2
LOMcs2G1Z4	101	503	12	2684	117	43	44.8	0	−6.35	−3.12	−0.12	−0.63	0	2.035	cs2
LOMcs2G2Z3	1337	6683	19	1323	197	103	101.2	0							cs2
LOMcs2G2Z3	1337	6683	22	1318	192	89	100.4	0	−4.97	−4.43	−14.46	−0.8	0	1.122	cs2
LOMcs3G1Z3	4084	81683	51	995	111	138	56.3	3.4							cs3
LOMcs3G1Z3	4084	81683	51	995	110	137	56.2	3.4	−0.29	−0.12	−1.11	−0.11	0	2.417	cs3
LOMcs3G1Z4	138	2768	13	474	80	125	25.4	0							cs3
LOMcs3G1cZ4	138	2768	16	472	78	122	24.8	0	−1.76	−2.51	−3.37	−0.67	0	0.701	cs3
LOMcs3G2Z3	351	7014	11	553	100	157	61	0							cs3
LOMcs3G2Z3	351	7014	11	548	91	147	49.8	0	−5.32	−9.58	−10.09	−11.16	0	0.555	cs3
LOMcs4G1Z3	3891	155642	53	1063	96	157	37	17.1							cs4
LOMcs4G1Z3	3891	155642	53	1062	95	155	36.7	16.7	−0.95	−1.33	−1.85	−0.32	−0.41	0.714	cs4
LOMcs4G1Z4	144	5746	12	73	151	204	38.9	0							cs4
LOMcs4G1Z4	144	5746	23	56	120	161	30.5	0	−16.78	−31.25	−43.09	−8.37	0	0.537	cs4
VENcs2G1Z3	10456	52279	53	420	221	46	65.1	0							cs2
VENcs2G1cZ3	10456	52279	53	419	217	44	63.9	0	−0.42	−4.1	−1	−1.22	0	0.102	cs2
VENcs2G1Z3	10456	52279	53	415	217	41	63.6	0	−4.57	−4.31	−4.81	−1.51	0	1.06	cs2
VENcs3G1Z3	2436	48723	20	126	198	48	48.9	0							cs3
VENcs3G1Z3	2436	48723	20	123	198	46	48.9	0	−2.11	−0.21	−2.26	−0.02	0	10.048	cs3
VENcs4G1Z3	1333	53313	54	427	167	50	32.8	18.4							cs4
VENcs4G1Z3	1333	53313	54	426	165	49	32.4	18.2	−0.93	−1.92	−0.82	−0.43	−0.19	0.484	cs4
VENcs4G1Z3	1333	53313	54	422	162	46	31.7	18.2	−5.42	−4.91	−3.32	−1.12	−0.16	1.104	cs4
EROcs1G1Z3	962	2406	19	3737	283	244	219.1	0							cs1
EROcs1G1cZ3	962	2406	21	3600	270	225	212.9	0	−137.07	−12.66	−19.56	−6.2	0	10.827	cs1
EROcs2G1Z3	8518	42588	52	1439	112	148	58.3	0							cs2
EROcs2G1Z3	8518	42588	46	1437	111	146	57.7	0	−1.83	−1.26	−2.35	−0.55	0	1.452	cs2
EROcs3G1Z3	5419	108374	47	1391	82	132	40.2	0.8							cs3
EROcs3G1Z3	5419	108374	53	1390	81	125	40	0.8	−1.41	−0.71	−7.06	−0.28	0.01	1.986	cs3
EROcs3G2Z3	394	7878	5	669	83	64	37.6	0							cs3
EROcs3G2Z3	394	7878	13	630	78	59	35.7	0	−39.02	−4.74	−4.48	−1.91	0	8.232	cs3
EROcs4G1Z3	5787	231460	53	1046	89	126	23.1	20.9							cs4
EROcs4G1cZ3	5787	231460	53	1046	88	125	23.1	20.3	−0.13	−1.19	−1.39	0.02	−0.54	0.109	cs4
EROcs4G1Z3	5787	231460	53	1043	87	124	23.1	20	−2.76	−1.95	−2.72	−0.02	−0.89	1.415	cs4
EROcs4G2Z3	218	8711	6	1329	34	211	13.7	2.9							cs4
EROcs4G2Z3	218	8711	6	1324	32	210	13.7	2.3	−5.04	−1.51	−1.52	0	−0.64	3.338	cs4

CONTEXT	*FARM*	*SURF*	*CC*	*INC*	*CO_2*	*N*	*LAF*	*LAE*	*D.INC*	*D.CO_2*	*D.N*	*D.LAF*	*D.LAE*	*AC*	*cs*
EROcs4G3Z3	111	4432	5	1708	47	51	19.8	21.6							cs4
EROcs4G3Z3	111	4432	5	1706	44	48	19.8	21.2	−2.24	−2.08	−2.99	0	−0.41	1.077	cs4
MARcs2G3Z3	250	1250	7	391	74	106	30	0							cs2
MARcs2G3Z3	250	1250	7	312	57	78	24.9	0	−79.31	−16.39	−27.43	−5.1	0	4.839	cs2
MARcs3G1cZ3	432	8649	24	180	103	103	34.7	0							cs3
MARcs3G1Z3	432	8649	37	178	100	98	34	0	−2.2	−2.41	−4.06	−0.65	0	0.913	cs3
MARcs3G2Z3	819	16381	33	541	102	79	44.9	0							cs3
MARcs3G2Z3	819	16381	33	541	101	78	44.7	0	−0.05	−0.71	−0.14	−0.22	0	0.07	cs3
MARcs3G2Z3	819	16381	32	537	101	75	44.8	0	−3.66	−0.88	−3.5	−0.14	0	4.159	cs3
MARcs3G3Z3	108	2168	9	2319	225	366	68.2	92							cs3
MARcs3G3Z3	108	2168	15	2098	193	273	68.2	15.5	−220.38	−31.54	−92.96	0	−76.55	6.987	cs3
MARcs4G2Z3	223	8903	36	762	88	73	21.8	4.1							cs4
MARcs4G2cZ3	223	8903	41	761	86	70	21.8	3.6	−0.31	−1.8	−2.76	0	−0.51	0.172	cs4
MARcs4G2Z3	223	8903	36	759	86	69	21.7	3.6	−2.25	−1.9	−3.85	−0.07	−0.52	1.184	cs4
MARcs4G3Z3	377	15070	22	545	90	93	29.9	0.2							cs4
MARcs4G3Z3	377	15070	23	544	89	92	29.9	0	−0.52	−0.52	−0.83	0	−0.15	1	cs4
TOScs2G1Z1	533	2666	14	1862	249	166	87.2	0							cs2
TOScs2G1Z1	533	2666	15	1862	249	166	87.1	0	−0.01	−0.18	−0.06	−0.06	0	0.056	cs2
TOScs2G1Z1	533	2666	30	1852	248	164	86.8	0	−10.77	−1.55	−1.98	−0.33	0	6.948	cs2
TOScs2G1Z3	353	1767	13	293	70	89	21.9	0							cs2
TOScs2G1cZ3	353	1767	13	293	70	88	21.8	0	−0.24	−0.36	−0.69	−0.06	0	0.667	cs2
TOScs3G1Z1	171	3413	35	2002	149	158	62.2	29.3							cs3
TOScs3G1Z1	171	3413	29	1978	149	142	62.2	25.6	−24.52	−0.12	−15.46	0	−3.76	204.333	cs3
TOScs3G2Z1	266	5312	31	25	50	19	15.7	0							cs3
TOScs3G2Z1	266	5312	31	25	50	19	15.7	0	−0.02	−0.03	−0.02	−0.01	0	0.667	cs3
TOScs3G2Z3	85	1699	21	95	59	38	93.5	0							cs3
TOScs3G2Z3	85	1699	20	81	58	30	66.2	0	−14.21	−1.53	−7.98	−27.32	0	9.288	cs3
TOScs3G3Z3	229	4572	17	146	78	41	23	0							cs3
TOScs3G3cZ3	229	4572	17	145	78	41	22.9	0	−1.66	−0.19	−0.61	−0.11	0	8.737	cs3
TOScs4G1Z1	474	18945	29	1274	169	183	28.4	51.2							cs4
TOScs4G1Z1	474	18945	37	1210	156	155	28.2	42.3	−64.13	−12.27	−28.19	−0.15	−8.92	5.227	cs4
TOScs4G2Z1	269	10773	26	166	52	47	11.2	0.9							cs4
TOScs4G2Z1	269	10773	26	165	52	45	11	0.9	−1.03	−0.5	−2.52	−0.15	0	2.06	cs4
TOScs4G2Z3	409	16378	26	178	63	45	15.7	1.1							cs4
TOScs4G2Z3	409	16378	26	178	62	45	15.7	1.1	−0.04	−0.16	−0.09	−0.04	0	0.25	cs4
TOScs4G2Z3	409	16378	26	169	62	42	15.6	1.1	−9.27	−0.48	−2.88	−0.05	−0.04	19.313	cs4
TOScs4G3cZ3	49	1977	18	87	81	35	21.3	0							cs4
TOScs4G3Z3	49	1977	18	82	74	30	19.5	0	−5.34	−6.79	−5.59	−1.85	0	0.786	cs4
ABRcs1G2Z3	305	763	18	711	198	52	154.1	0							cs1
ABRcs1G2Z3	305	763	18	711	198	52	154	0	−0.25	−0.29	−0.11	−0.1	0	0.862	cs1
ABRcs2G1Z3	439	2195	32	1100	240	52	169.8	0							cs2
ABRcs2G1Z3	439	2195	28	1100	240	52	169.4	0	−0.19	−0.71	−0.17	−0.4	0	0.268	cs2
ABRcs2G1Z3	439	2195	29	1072	234	48	166.6	0	−28.56	−6.32	−4.02	−3.28	0	4.519	cs2
ABRcs2G2Z1	42	211	24	861	226	23	108.2	0							cs2
ABRcs2G2cZ1	42	211	24	782	97	10	25.3	0	−78.85	−128.91	−12.76	−82.93	0	0.612	cs2
ABRcs2G2Z3	808	4042	38	509	163	37	99.4	0							cs2
ABRcs2G2Z3	808	4042	38	507	161	37	99.4	0	−2.03	−1.84	−0.51	−0.01	0	1.103	cs2
ABRcs3G1Z1	51	1026	10	836	148	61	50.1	13.7							cs3
ABRcs3G1Z1	51	1026	10	833	142	59	48.2	13.7	−3.02	−5.7	−1.55	−1.94	0	0.53	cs3
ABRcs3G2Z3	244	4873	37	2778	162	42	35.7	22.2							cs3
ABRcs3G2Z3	244	4873	37	2770	162	40	35.9	22.2	−8.3	−0.48	−2.15	0.17	0	17.292	cs3
ABRcs4G2Z3	43	1740	37	339	115	30	11.1	26.9							cs4
ABRcs4G2cZ3	43	1740	37	193	89	21	11.1	18.2	−145.74	−26.47	−8.23	0	−8.62	5.506	cs4
LAZcs1G1Z2	421	1053	16	3929	106	36	553.2	0							cs1
LAZcs1G1Z2	421	1053	20	2976	90	25	481	0	−952.32	−16.26	−10.5	−72.22	0	58.568	cs1
LAZcs3G1Z1	430	8608	32	2479	134	16	112.9	68.2							cs3
LAZcs3G1Z1	430	8608	32	2478	134	16	112.9	68.2	−0.38	−0.27	−0.05	0	0	1.407	cs3
LAZcs3G2Z3	980	19607	42	120	103	26	30.7	1.6							cs3
LAZcs3G2Z3	980	19607	41	114	103	25	30.1	1.6	−5.48	−0.69	−1.07	−0.66	0	7.942	cs3
LAZcs4G1Z1	806	32246	43	1283	52	19	26.7	51.4							cs4
LAZcs4G1cZ1	806	32246	43	1281	52	19	26.6	51.1	−1.79	−0.06	−0.15	−0.13	−0.21	29.833	cs4
LAZcs4G2Z3	49	1941	12	181	65	76	15.7	0							cs4
LAZcs4G2Z3	49	1941	13	164	58	72	13.4	0	−16.73	−7	−4.32	−2.26	0	2.39	cs4
CAMcs2G1Z2	745	3723	27	2059	293	119	194.5	29.5							cs2
CAMcs2G1Z2	745	3723	31	2045	286	112	186	28.3	−14.32	−7.07	−6.91	−8.52	−1.22	2.025	cs2
CAMcs2G1Z3	210	1050	23	1645	223	34	231.1	0							cs2
CAMcs2G1Z3	210	1050	16	1640	211	32	231.1	0	−5.5	−11.4	−1.75	0	0	0.482	cs2
CAMcs2G1Z3	210	1050	28	1355	119	16	141.1	0	−290.11	−104	−18.18	−89.95	0	2.79	cs2
CAMcs2G2cZ3	800	4000	25	1231	83	21	307.8	0							cs2
CAMcs2G2Z3	800	4000	29	1229	80	20	305.8	0	−1.42	−2.34	−1.39	−2.04	0	0.607	cs2
CAMcs3G1Z1	195	3890	14	1875	72	74	49.9	34.4							cs3
CAMcs3G1Z1	195	3890	15	1806	40	60	35.6	34.4	−69.2	−31.89	−14.58	−14.38	0	2.17	cs3
CAMcs3G1Z3	296	5922	31	699	181	32	123.3	22.7							cs3
CAMcs3G1Z3	296	5922	33	689	178	31	122.6	22.7	−9.47	−2.6	−1.22	−0.73	0	3.642	cs3
CAMcs3G2Z3	159	3190	18	1147	99	47	85.3	10.8							cs3
CAMcs3G2Z3	159	3190	19	1145	98	45	84.8	10.8	−1.78	−0.91	−1.55	−0.59	0	1.956	cs3
CAMcs4G2cZ1	32	1261	11	3165	26	145	32.9	129.5							cs4
CAMcs4G2Z1	32	1261	11	2915	21	133	32.9	110.3	−249.46	−4.81	−12.02	0	−19.23	51.863	cs4

CONTEXT	*FARM*	*SURF*	*CC*	*INC*	*CO_2*	*N*	*LAF*	*LAE*	*D.INC*	*D.CO_2*	*D.N*	*D.LAF*	*D.LAE*	*AC*	*cs*
PUGcs2G1Z1	2184	10922	29	3719	162	40	135	122.2							cs2
PUGcs2G1Z1	2184	10922	29	3719	162	40	135	122.1	−0.25	−0.3	−0.12	0	−0.1	0.833	cs2
PUGcs2G1Z2	1459	7296	13	1692	177	76	91.9	17.9							cs2
PUGcs2G1Z2	1459	7296	25	1659	152	71	84.8	17.7	−33.27	−25.71	−4.77	−7.1	−0.21	1.294	cs2
PUGcs2G1Z2	1459	7296	25	1572	146	61	82.9	17.7	−86.75	−5.96	−10.62	−1.78	−0.0	14.555	cs2
PUGcs2G1Z2	1459	7296	25	1318	129	54	97.3	15.2	−253.77	−16.18	−7.40	14.32	−2.43	15.684	cs2
PUGcs2G1cZ2	1459	7296	25	678	104	53	29.9	14.5	−640.08	−25.59	−0.69	−67.46	−0.77	25.013	cs2
PUGcs2G2Z3	366	1831	6	195	77	31	41.5	0							cs2
PUGcs2G2Z3	366	1831	6	195	77	31	41.3	0	−0.11	−0.69	−0.13	−0.21	0	0.159	cs2
PUGcs2G2Z3	366	1831	6	168	76	27	41.1	0	−27.48	−1.65	−4.29	−0.42	0	16.655	cs2
PUGcs3G1Z1	1081	21617	26	482	127	25	39.6	81.7							cs3
PUGcs3G1Z1	1081	21617	26	482	126	24	39.6	81.2	−0.44	−1.21	−0.49	0	−0.41	0.364	cs3
PUGcs3G1Z1	1081	21617	26	480	125	24	39.6	81	−2.02	−1.88	−0.83	0	−0.64	1.074	cs3
PUGcs3G1Z2	556	11112	13	1877	166	70	78.1	37.8							cs3
PUGcs3G1cZ2	556	11112	13	1822	163	65	76.7	37	−55.62	−2.72	−5.76	−1.38	−0.84	20.449	cs3
PUGcs3G1Z3	1714	34275	26	511	81	47	39.5	0							cs3
PUGcs3G1Z3	1714	34275	26	505	79	46	39.2	0	−5.65	−1.29	−1.06	−0.32	0	4.38	cs3
PUGcs4G1Z1	738	29512	14	2142	231	50	28	121.3							cs4
PUGcs4G1Z1	738	29512	14	2141	230	49	28	120.7	−0.75	−1.54	−0.84	0	−0.57	0.487	cs4
PUGcs4G1Z1	738	29512	14	2140	229	49	28	120.6	−1.57	−1.88	−1.02	0	−0.69	0.835	cs4
PUGcs4G1Z3	306	12227	15	499	113	214	37.2	33.1							cs4
PUGcs4G1Z3	306	12227	15	498	111	213	37.2	32.6	−1.91	−2.07	−1.7	0	−0.51	0.923	cs4
PUGcs4G2cZ3	292	11681	11	408	71	58	28.8	0							cs4
PUGcs4G2Z3	292	11681	11	356	60	44	25.6	0	−52.11	−10.25	−14.05	−3.11	0	5.084	cs4
CALcs2G2Z1	508	2538	12	709	147	7	59.9	0							cs2
CALcs2G2Z1	508	2538	12	703	144	7	58.8	0	−6.11	−3.22	−0.36	−1.12	0	1.898	cs2
CALcs3G2Z1	371	7413	9	791	231	3	67.8	0							cs3
CALcs3G2Z1	371	7413	9	790	231	3	67.6	0	−0.38	−0.66	−0.04	−0.23	0	0.576	cs3

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