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# Assessment of climate change impact on viticulture: Economic evaluations and adaptation strategies analysis for the Tuscan wine sector

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**Abstract**

Climate change is expected to have a significant impact on various economic sectors (IPCC, 2007) but an especially large one on agriculture because animal and crop growth are heavily influenced by weather conditions during their life cycles. In this paper, a multidisciplinary approach is developed that jointly uses economic and bio-climate models to evaluate the impact of climate change on viticulture in Tuscany (central Italy). Then a model is used to evaluate the likelihood of adoption of various adaptation strategies.


*Keywords:* Wine; Climate change; Adaptation strategies

## 1. Introduction

Many methodological approaches have been proposed in the literature for the identification and evaluation of damage caused by climate change, with the aim of developing adaptation and mitigation strategies and policies. In this paper, following a proposal by the European Commission in a White Paper, "Adapting to Climate Change: towards a European Framework for Action" (Commission of the European Communities, 2009), the risk of damage from climate change is considered as a consequence of two factors: the vulnerability of the examined system and its ability to adapt. *Vulnerability* (IPCC, 2007) refers to the susceptibility of a system to the negative effects of climate change. *Ability to adapt* refers to the ability of a system to implement measures to reduce future potential damage. Overall, the induced changes are destined to alter the ideal environment of vocational production, with effects that not only jeopardise the possibility of continued cultivation of certain products in certain regions but also push farms to introduce organisational and managerial changes to adjust their production systems to the changing conditions. The latter will have consequences on both processes and products that can be summarised, respectively, as follows:

– the adoption of new "ways to produce," often associated with higher production costs;
– the assessment and possible repositioning of products in markets (possibly extending to changes in target markets and a changed view of the competition, as a consequence of changes in the quality and quantity of output).

According to this approach, if production scenarios related to climate change are linked to an objective view of the local conditions that will allow for the cultivation of vineyards and the production of wine in the future,

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adaptation strategies of farms will be linked to the subjective way in which farms respond to external stimuli, according to a personal objective function that inspires their choices.

The assessment of the vulnerability of cultivation has been the object of numerous studies based on eco-physiological models. A review of these studies is found in White et al., 2011. Most of the examined models, however, do not assess the risk of topsoil loss, and they view variations in climate conditions as a source of incremental production variability. Furthermore, these models cannot be applied to different species. More recently, to overcome these limits, risk assessment models based on the effect of bioclimatic variables in relation to agro-habitat cultivation have become more popular (Barney and Di Tomaso, 2010). These models were also applied, to good effect, to cultivation in the Mediterranean area (Moriondo et al., 2008). Models based on bioclimatic variables were also applied to the assessment of quality loss risk in wine production (Grifoni et al., 2006; Jones, 2006).

Regarding adaptation strategies, Antle et al. (2004) propose a theoretical approach for the economic study of production systems related to climate change, based on the probability of endogenous adaptation by farms. Such a model has the advantage of representing spatial variations and interactions of both biophysical and economic variables in adaptation strategies.

Currently, realistic adaptation processes remain poorly understood and hard to quantify (Smit and Pilifosova, 2001). Although some recent progress has been made in this direction (IPCC, 2007), the extreme complexity of relationships and consequent behaviours of farmers are still difficult to fully understand. To identify vulnerabilities of farming systems and to develop ad hoc adaptation policies, it is essential to better understand the processes by which farmers adapt to climate change. Models for understanding and measuring the determinants of farmers' adaptation behaviours remain difficult to formulate, but an important step in this direction is made in Below et al. (2012): in their study, an activity-based adaptation index (AAI), which explores the relationship between socio-economic variables and adaptation behaviours of farmers, is proposed.

Although wide literature has developed in recent years, the evaluation of vulnerability, with or without adaptation of cultivation, with highly defined territorial detail remains difficult. This observation is especially true given the significant uncertainty that exists regarding the impact of climate change on agri-ecosystems, as well as the uncertainty that exists regarding the capacity of the socio-economic system to implement policies and managerial adaptation actions. The toughest challenge in the adaptation process will be how farmers respond "culturally" to changes in the "identity" of certain regions caused by the mutation of the ampelographic base and of quality characteristics (both technical and functional) of the wines. To achieve such adaptations, a crucial role will be played by attitude, managerial dynamism and technical and agronomical skill, attributes not easily incorporated into a statistical and/or deterministic model. Market reactions are also difficult to incorporate into a model because of the unpredictability of consumer expectations and of the behaviour of direct competitors. The aim of this work is to propose an innovative probabilistic methodology that explicitly considers those uncertainty factors, which are inevitable in the assessment of such complex variables. In particular, the approach integrates an evaluation system, coherent from an economic point of view, of models of the vulnerability of the agri-ecosystem and assessment models, based on the new Jøsang subjective probabilistic logic theories; such integration allows us to consider the effect of socioeconomic variables for each farmer on the probability that each will take managerial adaptation actions. The approach will be implemented in a Geographic Information System (GIS) using high-resolution economic, territorial and census data and applied to Tuscan viticulture, in particular to the Siena province.

## 2. The model

Let $v(x_0)$ be the value of agricultural production v per unit of time (year) and land (hectare), with $x_0$ the vector of data that describe the bioclimatic environment of cultivation. The effects of climate change are observed in the mutation of the values in the vector x: $x_0 \rightarrow x_1$ jeopardising the bioclimatic characteristics that guarantee local production potentials and changing the value of production in terms of both quantity and, especially, quality and without adaptation managerial actions being undertaken.

Then let $p(y||x_1)$ be the probability of obtaining a value of wine production at least equal to $v(x_0)$ without adaptation managerial actions being undertaken. In probabilistic terms, the vulnerability, without adaptation, of wine production, $ECVN$, can be expressed in terms of expected value as:

$$ECVN = p(y||x_1)v(x_0) + [p(y||x_1) - 1]v(x_1) \quad (1)$$

In case that the farmer has to stop production as a consequence of an insufficient profitability that is unable to cover fixed and variable costs, the value of production $v(x_1)$ will be equal to 0.

If the wine farmer is able to implement actions to adapt to climate change, these $x{:}x_0 \rightarrow x_2$ actions will result in direct costs, such as higher production expenses, and/or indirect costs in the form of lost revenues equal to $c(x_2)$ and the production value will reach again the level $[v(x_0) - c(x_2)]$. On the other hand, if the farmer is not able to implement actions to adapt to climate change, the expected production value will be equal to $ECVN$. If $p(y||x_2)$ is the probability that the farmer is able to reach again the production level $v(x_0) - c(x_2)$ as a consequence of the implementation of adaptation actions, the vulnerability with adaptation of wine production, $ECVA$, can be expressed in terms of expected value as:

$$ECVA = p(y||x_2)[v(x_0) - c(x_2)] + [p(y||x_2) - 1] \quad ECVN. \tag{2}$$

Adaptation actions will be an efficient decisional strategy if $ECVA \geq ECVN$.

In the probabilistic logic, $p(y_1||x_1)$ and $p(y_2||x_2)$ are called conditional probabilities (Jøsang, 2002). Conditional probabilities relate to conditional propositions which typically are in the form "IF $x$ THEN $y$", where $x$ indicates the antecedent and $y$ the consequent. In this case study $(y_1||x_1)$ implies the following proposition: "IF *the habitat of vine changes because of climate change* THEN *it is possible to maintain the value of production*". On the other hand, $(y_2||x_2)$: "IF *the farmer implements adaptation actions because of climate change* THEN *it is possible to maintain the value of the production*". The idea of having a probability connection between an antecedent and a consequent can be traced back to Stalnaker (see Jøsang, 2002) in the form of the so called Stalnaker's Hypothesis, formally expressed as: $p(\text{IF } x \text{ THEN } y) = p(y||x)$. In probability calculus, binomial conditional deduction is expressed as:

$$p(y||x) = p(x)p(y|x) + p(\neg x)p(y|\neg x) \tag{3}$$

where the terms are interpreted as follows: $p(y|x)$, probability of y given x is TRUE; $p(y|\neg x)$, probability of y given x is FALSE, p(x), probability of the antecedent x; $p(\neg x)$, complement probability $= 1 - p(x)$; $p(y||x)$, derived probability of consequent $y$.

The variables that impact $p(x_1)$ are exclusively bioclimatic in nature, and in this study they have been estimated using an ecological niche model. Thanks to these models, for a given vine hectare, it is possible to estimate the probability $p(x1)$ of an alteration in the *terroir*, as a consequence of an hypothesis of change in the main important climate variables that affect the vine habitat. The used method is described in par. 2.1.

On the other hand, the variables that influence the probability $p(x_2)$ that a farmer is able to adopt effective adaptation actions depend on the socioeconomic characteristics of the farmers and the organisation of the single farms:

$$p(x_2) = f(x', x'', x''', \ldots) \tag{4}$$

with $x'$, $x''$, $x'''$ as the socioeconomic variables. It is not possible to estimate the function $f(.)$ with statistical methods, since the past lacks in events that are comparable to the future climate change. The only solution to this is to estimate with empirical methods that are able to collect in a rational way experiences and knowledge coming from literature or from opinions of the experts of the sector. To explicitly consider the uncertainty conditions that characterise the issues at hand, the model was based on Jøsang's principles of subjective logic. The used methodology is explained in Section 2.2.

The identification of the $p(y|x_1)$, $p(y|\neg x_1)$, $p(y|x_2)$ and $p(y|\neg x_2)$, as well as the estimation of the economic value $c(x_2)$, is under a high level of uncertainty. Those variables depend on the conditions, hardly predictable a priori, in which the farmer will have to perform. In this situation, the existing literature on the evaluation of the impacts due to climate change has usefully applied analyses through explorative scenarios based on the scenario-axis technique. The methodology is explained in section 2.3.

Lastly, Fig. 1 shows the general scheme of the study.

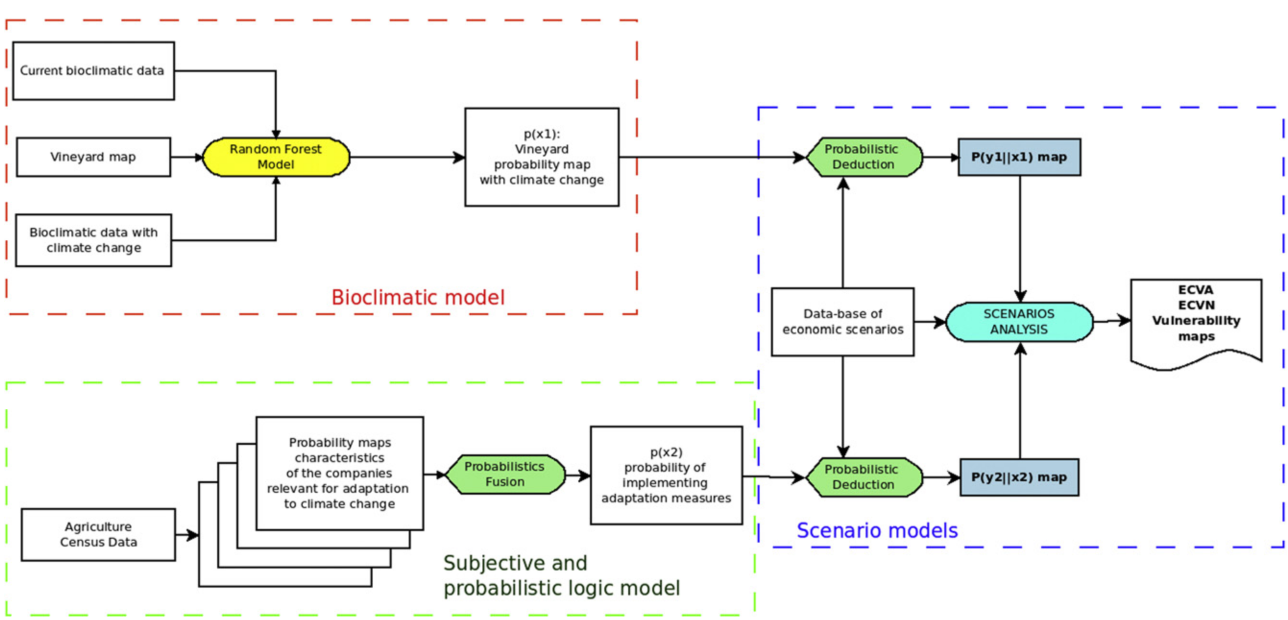


Fig. 1. Flux diagram of the applied procedure.

### 2.1. The use of bioclimatic models and the assessment of agroecosystem vulnerability

The assessment of viticulture vulnerability is a complex issue, as the achievement of high quality standards depends upon the interaction of climate, soil and agronomic and oenological techniques and practices.

The term *terroir* concisely and effectively expresses the relationship between the plant and the environment for the specific eco-pedology and cultivation conditions that determine the diversity and originality of the wines produced in a certain area. In this phase of the research, we have tried to build a model of ecological suitability, with specific reference to the concept of *terroir*, as the climate–soil–vine–cultivation technique interaction.

The use of statistical models in agro-ecology has developed in the last decade, largely thanks to progress in the field of geographical information systems (GIS) and the ease of retrieval of geo-referenced environmental databases. The last decade has witnessed the development of data mining methods, originally linked to the informatics field, of statistics and artificial intelligence. One of the more recently developed data mining techniques is the Random Forests (RF) technique, introduced by Breiman (2001). With implementation of the RF model, it is possible to obtain the probability that a particular area is suitable for vine cultivation with traditional agronomic techniques, given current bioclimatic variables. Furthermore, the application of this model to future scenarios allows us to determine the probability of vine cultivation in the future, using current techniques and given future climatic conditions.

To preserve the specific characteristics of the Tuscan *terroir*, the model was applied under a strictly local approach. The dataset used to build the random trees model was compiled by selecting 10,000 random geographical points corresponding to areas inside Controlled Designation of Origin (DOC) or Controlled and Guaranteed Designation of Origin (DOCG) zones, and 10,000 points in areas without vine cultivation. These points were associated with 19 bioclimatic variables from the Worldclim geodatabase. The dataset was divided into two subsets equal in dimension (5,000 points without vine cultivation and 5,000 points with other land use), one used for training and building the model and one used for validation testing. The values obtained though validation testing were used to verify the discriminating capability of the model, or, in other words, its attitude toward properly separate ‘‘Tuscan *terroir*’’ locales and ‘‘non *terroir*’’ locales.

### 2.2. The use of subjective logic and the assessment of adaptation probability

On the basis of the existing literature (Bernetti et al., 2006; Battaglini et al., 2009; Olesen et al., 2011), the probability $p(x_2)$ that a farmer is able to implement effective adaptation actions depends on his professional training and preparation, on his specialisation and on his capabilities of promptly reacting to new and unexpected situations. The variables that can contribute to the estimation of such probability are: $x^t$, educational qualification of the farmer; $x^a$, his age; and $x^s$, his experience in a farm specialized in a quality viticulture. The structure of the agricultural information in Italy does not allow to get information on the characteristics of the owner of a specific hectare of vine, but (as it is explained in detail in Section 3.3) only of the aggregated data referred to a minimum census territorial unit in order not to allow the identification of the land owner there to be included. In such a situation, $p(x_2)$ can be estimated as ‘‘the probability that the owner of a hectare of vine in a certain census unit is able to adopt effective adaptation actions’’. In the same way, the explanatory variables $x^t$, $x^a$ and $x^s$ have to be interpreted as ‘‘the probability that the owner of an hectare of vine in a certain census unit has an educational qualification/age/specialisation that makes him capable of adopting adaptation actions’’.

Thus, it is necessary to use a methodology that is able to: determine the specific contribution of the probabilistic variables $x^t$, $x^a$ and $x^s$ to the probability $p(x_2)$; aggregate them in a rational and coherent way in respect to the examined case study; and create a model for the uncertainty linked with the two previous operations. Such a methodology has been detected in the subjective logic of Jøsang.

Subjective logic (Jøsang, 2001, 2008) has been formalised with the aim of avoiding the need of precisely identifying the value of probability of all the possible events, considering the influence of uncertainty in terms of structures of incomplete knowledge. The core concept of subjective logic is the ‘‘subjective opinion’’ (or shortly ‘‘opinion’’). The opinion strictly derives from the concept of ‘‘belief’’ formulated by Dempster and Shafer (Bernetti et al., 2011), but with a closer relationship with the probability theory.

An opinion, which in its simplest form is a binomial opinion, can be defined as follows:

Let $X=\{x,\overline{x}\}$ indicate a structure or binary partition composed of the hypothesis $x$ and its negation $\overline{x}$. A binomial opinion is expressed by the ordered quadruple $\omega_x=(b,d,u,a)$, where $b$=belief: the belief mass supporting hypothesis $x$; $d$=disbelief: the belief mass supporting hypothesis $\overline{x}$; $u$=uncertainty: the belief mass that is not assigned; $a$=base rate: the base property that exists a priori in the absence of an assigned supporting belief mass; thus ‘‘$a$’’ represents the base probability when no evidence (a detected phenomenon, the advice of an expert, etc.) is identified that supports $x$ or QUOTE . The following relations exist: $b+d+u=1$ and $b,d,u,a\in[0,1]$.

One of the major merits of subjective logic is its close relationship to probability theory. In fact, it is also possible to express an opinion in probabilistic terms. Let us indicate an opinion $\omega=(b,d,u,a)$ and an opinion expressed in probabilistic terms as $\omega=(E,c,a)$, both on the binary partition X. The equivalence between the two demonstrations is defined as follows:

$$\begin{cases} E=b-au \\ c=1-u \end{cases} \Leftrightarrow \begin{cases} b=E-a(1-c) \\ u=1-c \end{cases} \quad (5)$$

Using (4), identifying the (subjective) degree of certainty $u$, it is possible to convert probabilistic values into Jøsang opinions.

For the conversion of the probabilistic variables $x^{t}$, $x^{a}$ and $x^{s}$ into the corresponding Jøsang opinions $\omega^{t}$, $\omega^{a}$ and $\omega^{s}$ an approach based on the fuzzy function has been used, with $u$ hypothesised to be constant. Fig. 2 shows the values of belief, disbelief and uncertainty obtained as a function of the expected values of the probabilities.

As subjective logic is a generalisation of logic and probability, opinions can be combined in complex knowledge structures. Jøsang (Jøsang, 2001; Jøsang et al., 2010) formulated a set of subjective logic operators, some corresponding to those of binary logic and probability theory and some belonging exclusively to subjective logic. The operators that are used in this study (see Fig. 1) are the probabilistic fusion, the probabilistic product and the probabilistic coproduct. Probabilistic fusion is applied when it is necessary to combine two independent subjective opinions supporting the same partition.

The rule of probabilistic fusion (Jøsang et al. 2010) is the following: if we indicate with $\omega^{A}$ and $\omega^{B}$ two opinions supporting the same binary partition $X$, the probabilistic fusion $\omega^{A\diamond B}$ is:

$$\text{Case I}: \text{For } u^{A}\neq 0 \ \vee \ u^{B}\neq 0:$$
$$\begin{cases} b^{A\diamond B}(x_i)=(b^{A}(x_i)u^{B}+b^{B}(x_i)u^{A})/(u^{A}+u^{B}-u^{A}u^{B}) \\ u^{A\diamond B}=(u^{A}u^{B})/(u^{A}+u^{B}-u^{A}u^{B}) \end{cases}$$
$$\text{Case II}: \text{For } u^{A}=0 \ \wedge \ u^{B}=0:$$
$$\begin{cases} b^{A\diamond B}(x_i)=\gamma^{A}b^{A}(x_i)+\gamma^{B}b^{B}(x_i) \\ u^{A\diamond B}=0 \end{cases}$$
$$\text{where} \begin{cases} \gamma^{A}=\lim_{\substack{u^{A}\to 0 \\ u^{B}\to 0}} \dfrac{u^{B}}{u^{A}+u^{B}} \\ \gamma^{B}=\lim_{\substack{u^{A}\to 0 \\ u^{B}\to 0}} \dfrac{u^{A}}{u^{A}+u^{B}} \end{cases} \quad (6)$$

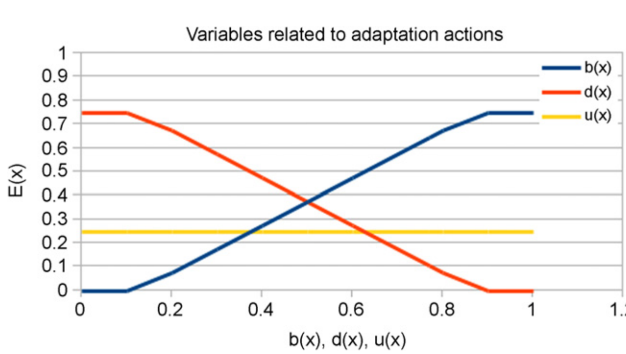

Fig. 2. *Belief*, *disbelief* and *uncertainty* as functions of probability.

Aggregating through the (6) the opinions $\omega^{t}$, $\omega^{a}$ and $\omega^{s}$ it was possible to calculate the opinion $\omega^{x2}$, which represents the possibility that a hectare of land is belonging to a farmer capable of implementing adaptation actions. Lastly, through (5) this opinion was converted into the corresponding probability $p(x_2)$.

### 2.3. *Economic evaluation and scenario analysis.*

Scenario exercises may be defined as being either exploratory, extrapolatory or normative in approach. Exploratory approaches create a stylised 'model' of a system and make projections for the system given assumptions about the determinants of change. Most scenario studies take an exploratory approach (Berkhout and Van Drunen, 2007). In literature many global scenarios share common intellectual roots, share convergent visions of the future (see Berkhout and Van Drunen, 2009) and have applied the scenario-axis technique (Van't Klooster and van Asselt, 2006). This technique comprises the identification of two key uncertainties that determine a graph with the subsequent axes. In each quarter of the co-ordinate system set-up by the key uncertainties narratives are drawn up. The main advantages of the scenario axis method are a degree of analytical rigour and the transparency of the process (Berkhout and Hertin, 2002); the number of generated scenarios (four) represents a compromise: two are too narrow, three lead to a best guess (the middle one) and more than four are too difficult to manage.

As shown in Fig. 3, the economic analysis carried out using the proposed method was based on the following uncertainty axes: (1) uncertainty about the reduction of production value caused by climate change and (2) uncertainty about the reduction of production value because of direct and indirect costs of adaptation actions. On the basis of existing literature (Orlandini et al.. 2006, Grifoni et al., 2006) and the opinion of sector experts, the vulnerability of the vines in economic terms is strongly influenced by occasional or permanent irrigation (this is also confirmed by the most important variables in the assessment of the bioclimatic model, see section 4.1). Symmetrically, adaptation costs are mainly influenced by the farm's possibility to have access to water. The costs related to the various adaptation actions can be divided in two categories: fixed and variable costs for investments (DC) aimed at adapting the vineyards to new climate conditions and indirect costs (IC) due to lost revenues (for decreased quantity or quality of grape and wine production). For each quadrant, because of the two kinds of uncertainties, there is a total economic impact (TEI) of the scenario:

$$\text{TEI}=\text{DC}+\text{IC} \quad [7]$$

According to Grothman and Patt (2005) and Olesen et al. (2011), the probabilities $p(y|x_1)$, $p(y|\neg x_1)$, $p(y|x_2)$ and $p(y|\neg x_2)$ (see eq.(3)) were respectively interpreted as risk perception (the first pair of probabilities) and

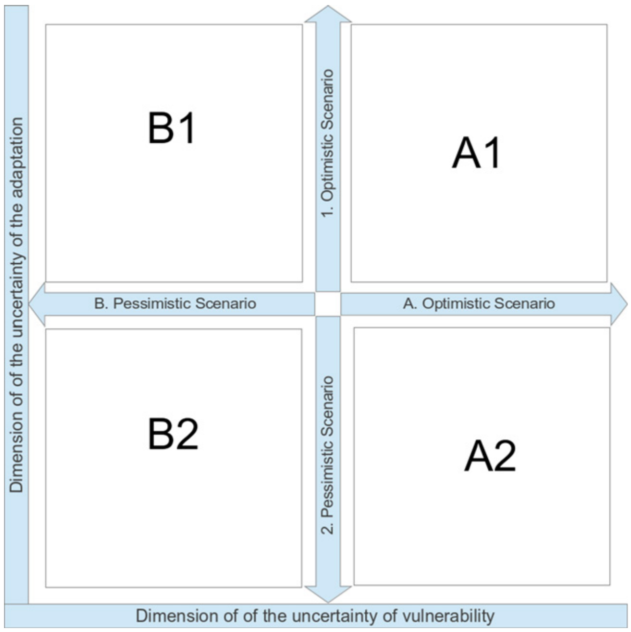


Fig. 3. Analysed scenarios.

perceived adaptive capacity (the second pair). Using this definition, the probabilities were assessed empirically and verified using the opinions of experts.

The intersection of the two axes generates four storylines.

(A1) This is an optimistic scenario, with a mild climate change and a high adaptation capability of the farm. There is a high probability of irrigation, considering that it might only be occasional. In this scenario, on the side of IC, production might remain a DOCG and might only suffer a slight decrease in quantity. On the side of DC, on the other hand, there is no need for a new vine planting, and there is only a cost increase due to different cultivation techniques and the creation of an irrigation system. The probability $p^{A1}(y|x_1)$ of maintaining the same value of wine production if the *terroir* change is TRUE is 0.5, and the probability $p^{A1}(y|\neg x_1)$ of maintaining the same value of wine production if the *terroir* change is FALSE is 0.9. The probability $p^{A1}(y||x_2)$ that the farmer can restore the same levels of production after adaptation actions is 0.9 and $p^{A1}(y|\neg x_2)$ is equal to $p^{A1}(y||x_1)$.

(A2) In this scenario, the hypothesis is optimistic about climate change and pessimistic about the possibility of access to irrigation. This means not setting an irrigation system, which will however allow the perpetuation of production activities because of only mild variations of climate. Thus, compared to the previous scenario, the IC are higher due to a decrease in production, but the DC are lower because no expenses for the setting of an irrigation system are necessary, just a forced change in the cultivation techniques. The probabilistic elements are set as follows: $p^{A2}(y|x_1)=0.5$, $p^{A2}(y|x_2)=0.8$ and $p^{A2}(y|\neg x_2)=p^{A2}(y||x_1)$.

(B1) In this scenario there is a pessimistic view about the effects of climate change and an optimistic view about the access to water and farm adaptation capability. Thus, the scenario includes a permanent irrigation system for the farms. Here IC are accounting for a high decrease of production, partially compensated by permanent irrigation; in this case, IC are higher than in the two previous scenarios as the DOCG production do not allow for permanent irrigation and the farms are obliged to turn to Typical Geographic Indication (IGT) productions with lower product value per quantity (in this case excluding any modifications to the current DOCG regulations). As for DC, they are high too, because of both cultivation technique modifications and the setting up of a permanent irrigation system. The probabilistic elements are set as follows: $p^{B1}(y|x_1)=0.1$, $p^{B1}(y|x_2)=p^{A1}(y|x_2)$ and $p^{B1}(y|\neg x_2)=p^{B1}(\mathrm{y}||\mathrm{x}_1)$.

(B2). This is a pessimistic scenario for both the effects of climate change and water access/irrigation possibility. These conditions lead to consider that, with no irrigation available, vine cultivation is possible only if the farmer plants new vine varieties and adopts new cultivation techniques. This is the scenario with the highest total costs, because of a decrease in quality production, since the farmer is producing IGT wine instead of DOCG wine, and a change in the vine cultivar, The probabilistic elements are set as follows: $p^{B2}(y|x_1)=0.1$, $p^{B2}(y|x_2)=p^{A2}(y|x_2)$ and $p^{B2}(y|\neg x_2)=p^{B2}(y||x_1)$.

## 3. The study area

### 3.1. The characteristics of the wine sector in Montalcino within the Siena province

With a surface area of 3821 km$^2$, Siena is the second largest Tuscan province in territorial extent. The agricultural sector comprises 8449 farms, 20% of total companies (Istat, 2012), covering 275,239.5 ha of total agricultural surface; thus, the rural component plays a very important role. Within this context, the wine sector is of primary importance, emblematic of the whole territory and contributing to the local economy as part of the agri-food sector and as a draw for tourism. The Siena province has always been the Tuscan area with the largest volume of wine cultivation (with 18,330.39 ha of vineyards, 31% of the regional total) and very important on a national scale, guaranteeing a wide supply of products, as evidenced by the many Geographical Indications (DOCGs, DOCs and IGTs) that cover the vine areas of the province. 880,000 hl of wine are produced in the province, 31% of the regional total.

Within the province, Montalcino represents one of the best expressions of excellence in Italian wine production. The cultivation of vine in this area dates back to the Etruscan days and since then the economy of the area has been heavily based on the production of wine and oil. 332 wine farms cover 3925 ha of vines (with an average farm size of 11.8 ha). Most of the production (more than 116,000 hl) is represented by DOC and DOCG wines, the most important and renowned of which is Brunello di Montalcino. The Brunello DOCG covers 2,020 ha of vines belonging to 311 farms, for a total production of about

80,000 hl per year and is the only DOCG in the area. Three DOCs (Rosso di Montalcino, Moscadello di Montalcino and Sant'Antimo) are produced in the Montalcino municipality along with the Tuscan IGT. Over 70% of the bottles of Brunello di Montalcino are exported, with the United States being its most important market (about 25% of total production). On the national market, Brunello is mainly sold in restaurants and wine shops, while only a small amount is distributed via major retail chains.

The choice of the Montalcino area as a case study is due to its absolute relevance in the context of Tuscan and Italian viticulture. Analysing such a territory may help shed some light into what climate change might mean for the wealthier and more prestigious and traditional wine areas of Italy (Fig. 4).

### 3.2. The climatic geodatabase

The probability of having a suitable habitat for vine in the current climate situation is subject to meteorological variables that have a great influence on the production response of vines and on the quality of the final product (both grapes and wine). In this perspective, using indexes that can describe some climate characteristics of the production environment supplies a useful instrument for agronomic and cultivation choices (Azzi, 1933). On this basis, the research was carried out using bioclimatic indexes. Among the most important researches on viticulture, Amerine and Winkler in the 1940s and 1950s used a bioclimatic index based on temperature to classify California in five zones with different vine growing vocations (Winkler et al., 1962). In the same period, Branas (1974), with the objective of highlighting production potentials of vine areas, proposed an index correlating effective average temperatures to the daily duration of sun exposure in favourable periods. Orlandini et al. (2006) used bioclimatic indexes derived from the HadCM3 scenario for the analysis of the effects of bioclimatic change on Brunello di Montalcino. Grifoni et al. (2006) used freely available meteorological information on the internet for the analysis of Italian wine quality. The authors state that "the analysis of large-scale meteorological information available on the Internet confirmed previously known relationships between wine quality and weather conditions, determined using data measured at field level". More recently, Jones and Alves (2012) used climatic data from the HadCM3

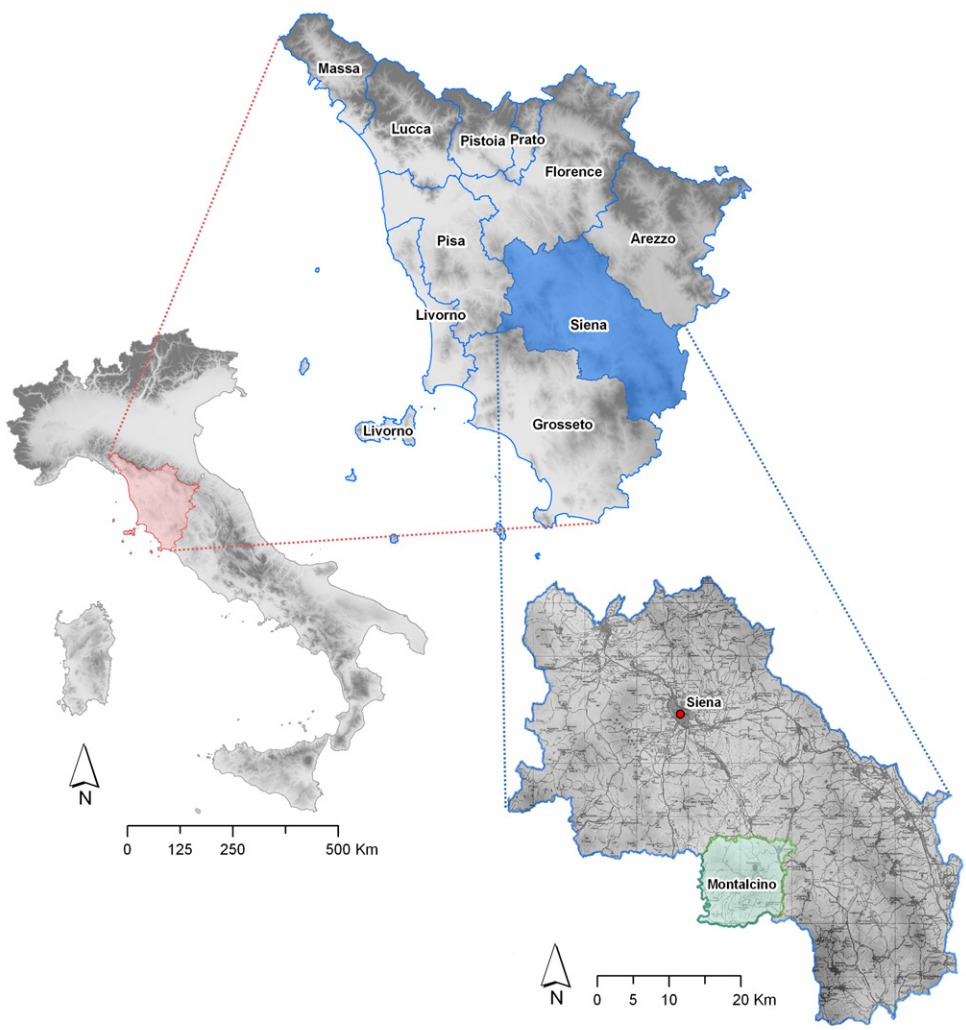


Fig. 4. The Siena province in the Italian and Tuscan context, with a focus on the Montalcino area.

scenario downscaled to 1 square kilometre in the Worldclim database for a regional assessment of the impact of climate change on wine production in the Douro Valley of Portugal.

Considering these researches, this study was based on bioclimatic indexes from Worldclim database. Worldclim is a set of cartographic layers containing climate data and climate change scenarios, with a 1 km$^2$ resolution. The layers contain interpolations of monthly data on precipitation, maximum, average and minimum temperature and 19 bioclimatic variables. The estimates of current bioclimatic conditions are derived from an average of climate values in the 1950–2000 period, while the climate change scenario was constructed using data from the IPCC4 HadCM3 (hccpr)—SRES B2A scenario for the year 2020. The bioclimatic indexes used in this study are as follows:

BIO1 = Annual Mean Temperature
BIO2 = Mean Diurnal Range (Mean of monthly (max temp–min temp))
BIO3 = Isothermality (BIO2/BIO7) ( × 100)
BIO4 = Temperature Seasonality (standard deviation × 100)
BIO5 = Max Temperature of Warmest Month
BIO6 = Min Temperature of Coldest Month
BIO7 = Temperature Annual Range (BIO5–BIO6)
BIO8 = Mean Temperature of Wettest Quarter
BIO9 = Mean Temperature of Driest Quarter
BIO10 = Mean Temperature of Warmest Quarter
BIO11 = Mean Temperature of Coldest Quarter
BIO12 = Annual Precipitation
BIO13 = Precipitation of Wettest Month
BIO14 = Precipitation of Driest Month
BIO15 = Precipitation Seasonality (Coefficient of Variation)
BIO16 = Precipitation of Wettest Quarter
BIO17 = Precipitation of Driest Quarter
BIO18 = Precipitation of Warmest Quarter
BIO19 = Precipitation of Coldest Quarter

### 3.3. Census data

Census microdata on agriculture in Italy have, as a primary characteristic, a “one to many” database structure, whereby for each farm record – that contains farmer and farm socioeconomic data – there corresponds one or more records indicating the land parcels belonging to the farm. For each parcel, a geo-referenced census unit is indicated. To guarantee anonymity, the locale of each parcel is identified with a relatively large census unit, so that one census unit can contain land parcels belonging to different farms. This practice necessitates transfer to territorial-level information that is not strictly geographic in nature. One possible consolidation probabilistic model is the following (Bernetti et al., 2006; Barreto and Hartkamp, 1999; Aalders and Aitkenhead, 2006). Let $m$ indicate parcels in census unit $i$ belonging to $n$ farms. Let $g'\{0,1\} \rightarrow x'$ indicate a farm's socioeconomic characteristics, expressed as a binary datum, so that it contributes to probability $p(x_2)$. The probability $p_i(x_i')$ that any one hectare of census unit $i$ belongs to a farm with characteristic $g$ is:

$$p(x') = \frac{\Sigma_m \left\{ \begin{matrix} S_{m,n} & if \; g = 1 \\ 0 & if \; g = 0 \end{matrix} \right\}}{\Sigma_m S_m} \quad (8)$$

The procedure is graphically shown in Fig. 5.

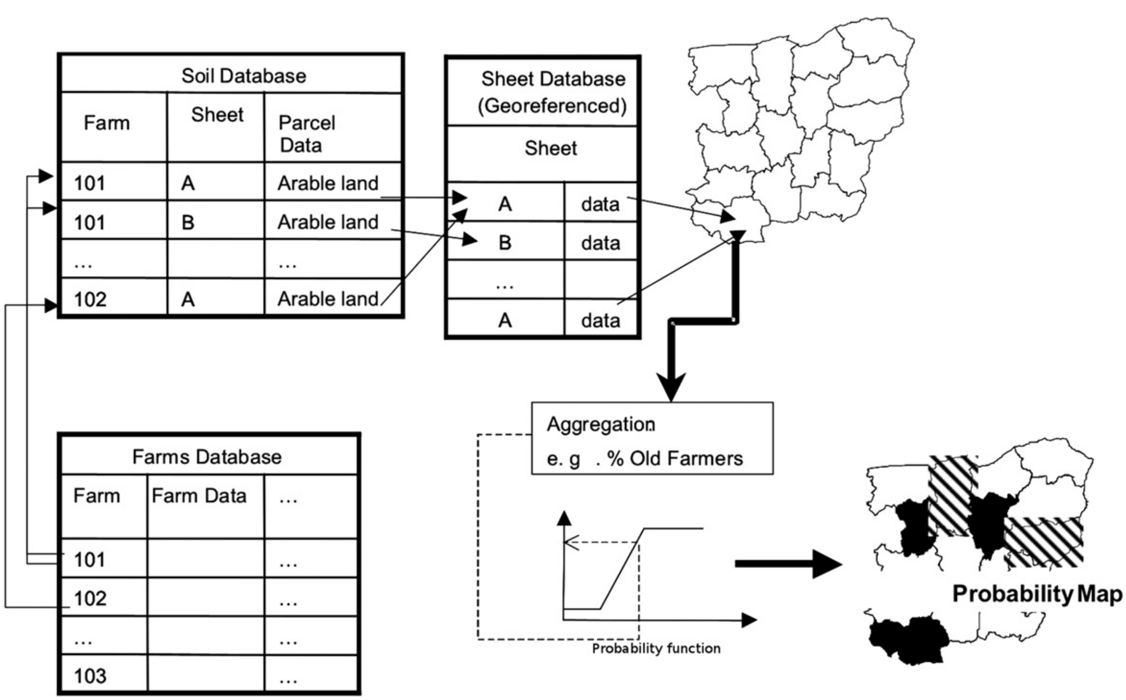


Fig. 5. Structure of the census geodatabase (Bernetti et al., 2006).

## 4. Results and discussion

### 4.1. The Random Forest method and the damage risk from climate change

The Random Forest model was used to assess the probability of the presence of viticulture, given the characteristics of the Tuscan *terroir*, both in the present and using the bioclimatic variables of scenario IPCC4. Regarding the assessment of the Random Forest model, Breiman (2001) proposes several methods to evaluate the importance of each variable in such a model. In this case, the importance was assessed using the reduction in the average decrease in the accuracy of prediction (prediction error) and ROC analysis. The first approach is based on the prediction error for all the variables for each tree diagram. The prediction error of a variable is assessed for each tree by the permutation of all the values of the variable. Fig. 6 shows the importance of the variables according to the average decrease of the accuracy of prediction. The results show that the most important variables are BIO7, Temperature Annual Range, BIO4, Temperature Seasonality; BIO2, Mean Diurnal Range, BIO12,

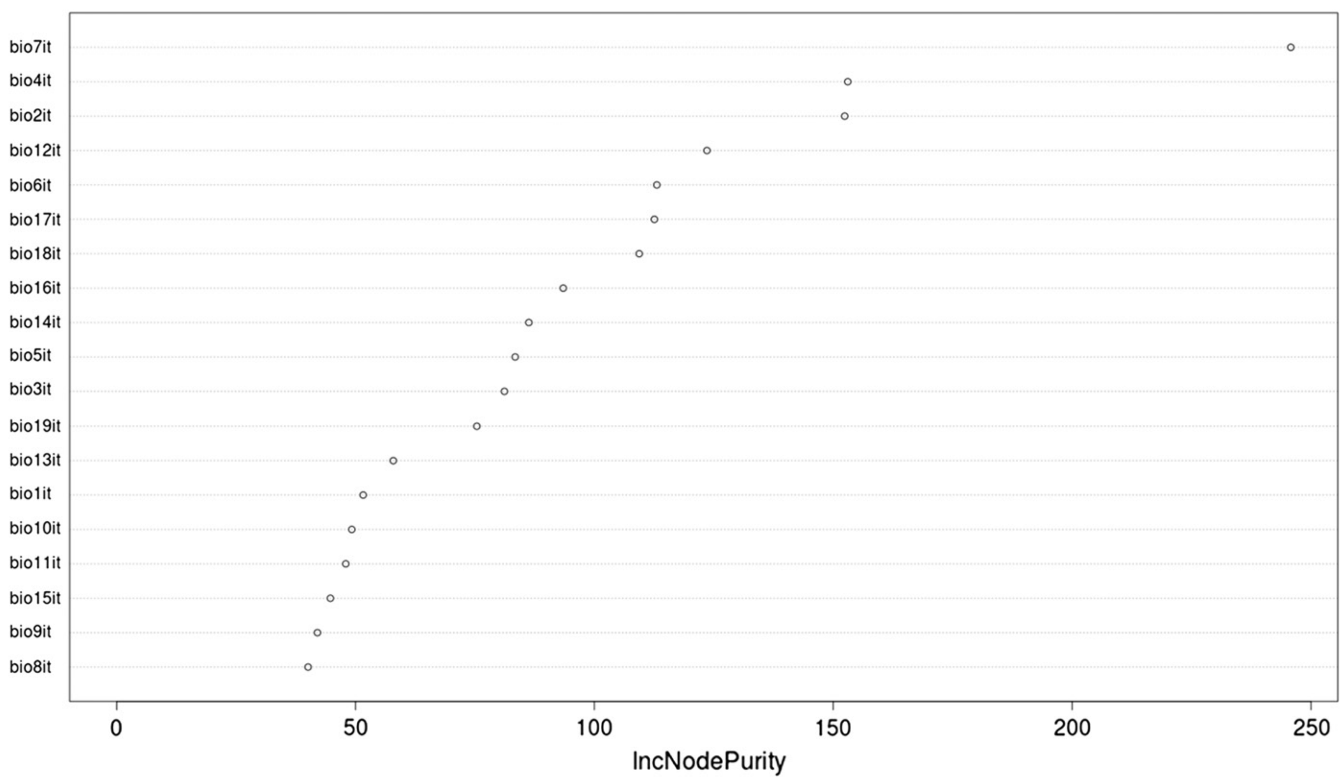


Fig. 6. Importance of the variables, according to the average decrease in the accuracy of prediction.

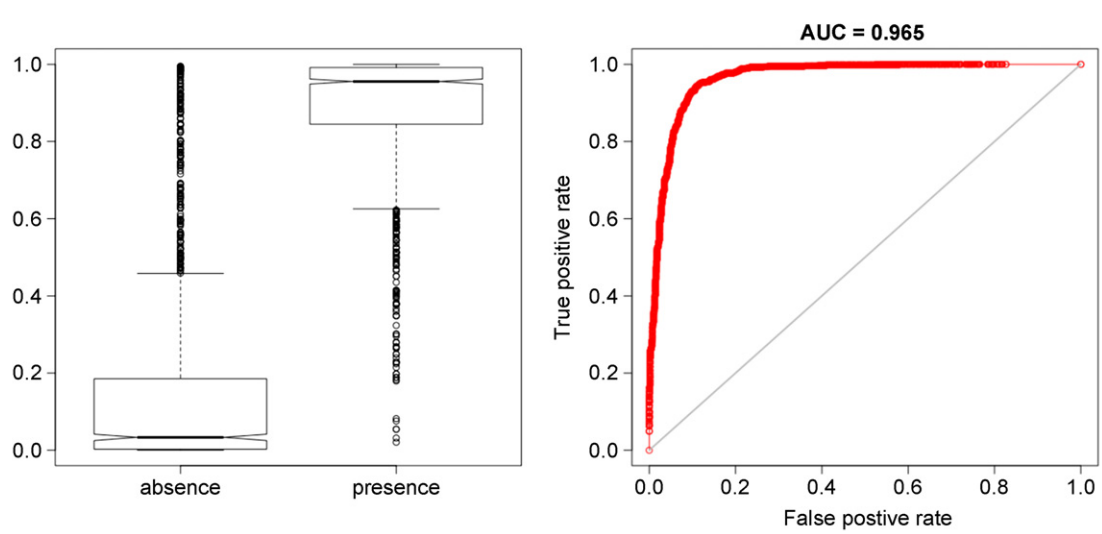


Fig. 7. Ranking performance statistics for the Random Forest model.

Annual Precipitation, BIO6, Min Temperature of Coldest Month, BIO17, Precipitation of Driest Quarter; and BIO18, Precipitation of Warmest Quarter. Beyond these variables, the index falls below 100.

The ROC analysis is carried out through the study of a function that, within the model, links the probability of obtaining a true positive result in the presence class to the probability of obtaining a false positive result in the absence class. From the ROC graph, it is possible to calculate the Area Under the Curve (AUC) that indicates the model's performance. According to the ranking proposed by Swets (1988), the AUC varies between 0.5 and 1, with a value of 0.5 for models with no ability to discriminate presence from absence and a value of 1 for models with perfect discriminating ability. The obtained model shows good ranking performances, as shown in Fig. 7.

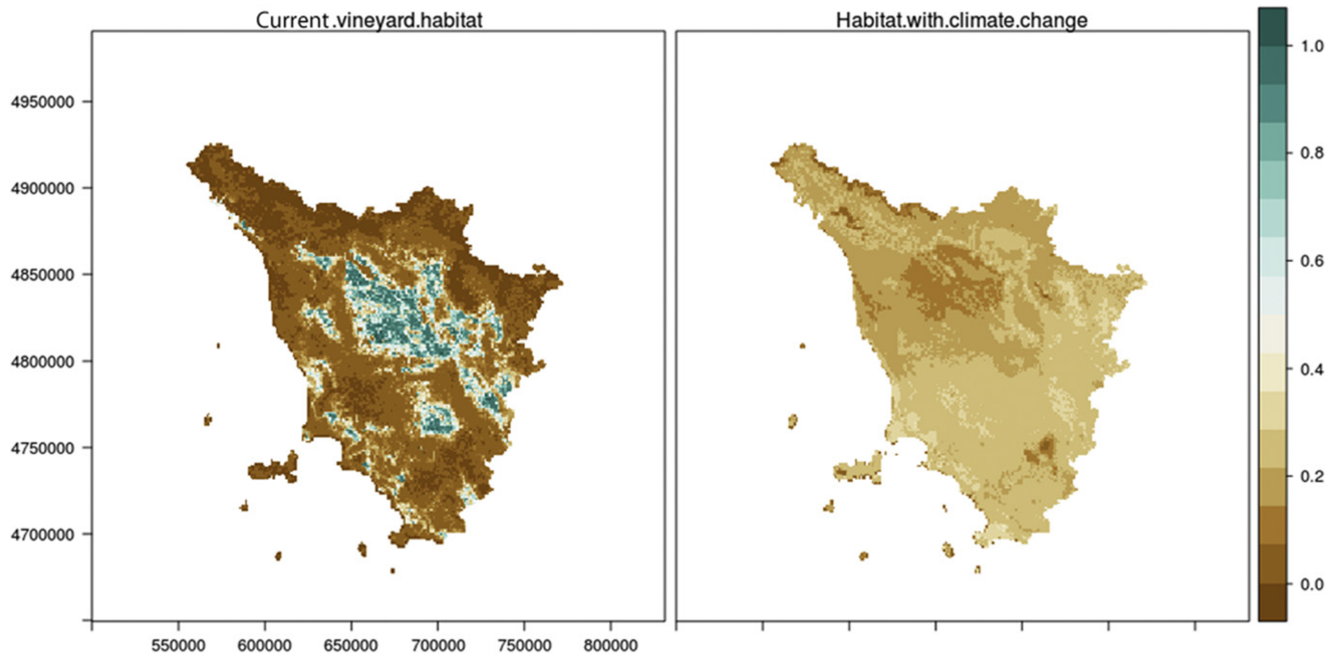


Fig. 8. Current vineyard habitat and climate change results of the Random Forest model in Tuscany.

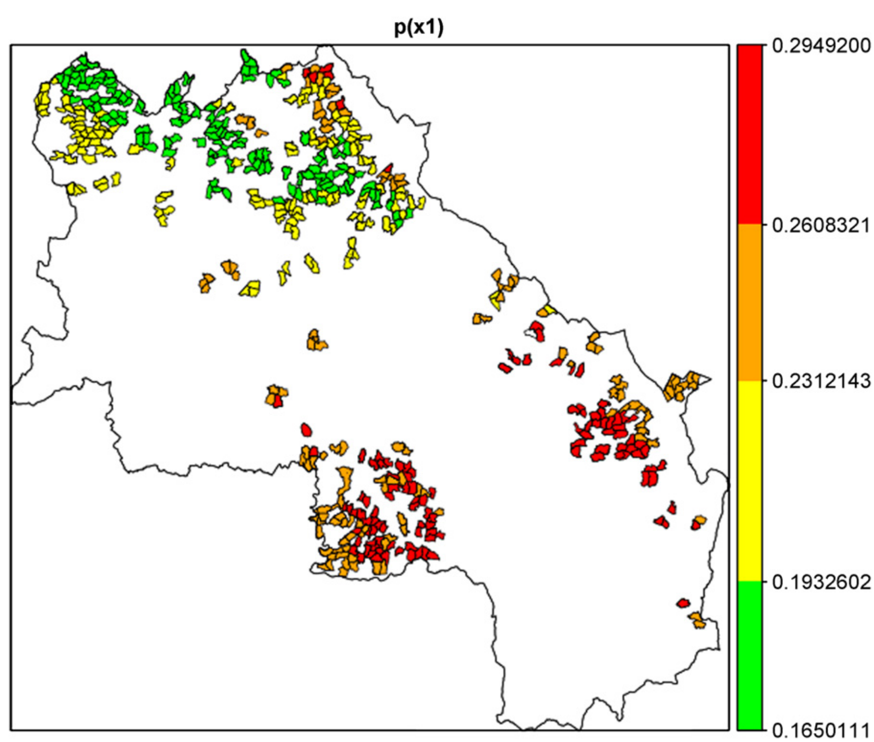


Fig. 9. Map of the probability $p(x_1)$ to have a favourable habitat for typical vines (*terroir*) as a consequence of climate change.

The probabilities of a habitat suitable for vine cultivation, under current predictions and with climate change, are shown in Fig. 8. Currently, the most suitable zones are mainly in the Chianti and Chianti Classico areas and in the Siena province. On the other hand, with respect to vine cultivation with climate change and current cultivation techniques, the map on the right shows that the probability decreases considerably. In fact, the maximum probability in Tuscany is 40%, with an average value of only 22%.

Matching the results with the census units with vine in the Siena province, it is possible to draw a map (Fig. 9) of the average probability of habitat change $p(x_1)$. The map is drawn with different colours for each quartile in the frequency distribution. As the map shows, probabilities are contained within a minimum level of 0.16 and a maximum of 0.3. The (relatively) higher values, all above the median and most above the third quartile, are in the Brunello di Montalcino and the Nobile di Montepulciano area, while a critical situation is observed in the Chianti Classico area, with almost all values below the median (0.23).

### 4.2. The adaptation possibility for the wine sector

The map showing the probability $p(x_2)$ of obtaining the same level of wine production before and after climate change, assuming adaptation measures are undertaken by farms, was derived using the opinion fusion rule using (6) and converted to probabilities using (3). The elaborations show that adaptation actions lead to a 61% probability of maintaining current levels of income, with quartiles (see the colour classes in Fig. 10) of 52% and 80%.

On a territorial scale, the Montalcino area seems to present higher possibilities to have farmers with the ability to implement effective adaptation strategies.

### 4.3. Economic scenarios

The economic results, as shown in Figs. 11 and 12, are strongly influenced by the adaptation element. As a matter of fact, scenarios A1 and A2, which do not imply the shift toward an IGT production, are more economically efficient

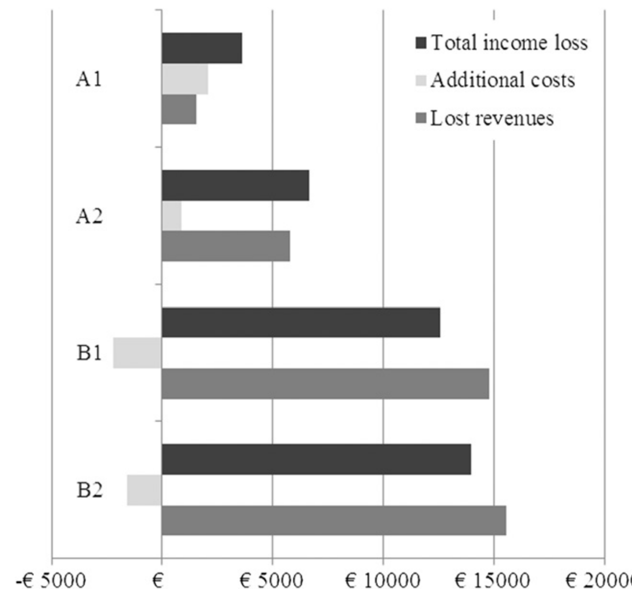


Fig. 11. Additional costs (direct costs), lost revenues (indirect costs) and total income loss for analysed scenarios.

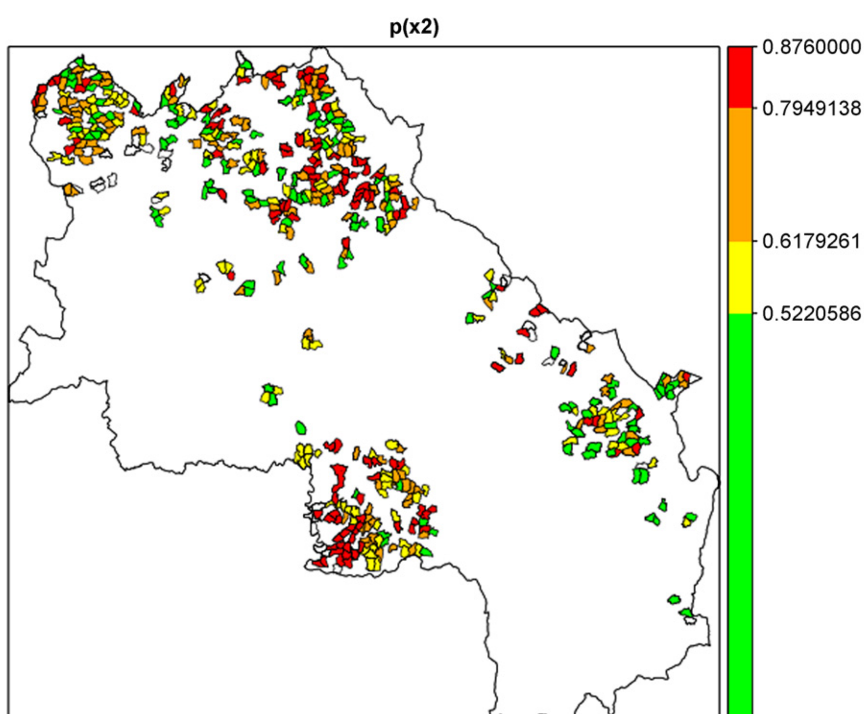


Fig. 10. Probability map $p(x_2)$.

than the corresponding ECVN alternatives. The expected decrease in the production value for scenario A1 seems kept down, resulting in an average of 22%, with quartiles of 20% and 23%. For scenario A2'', instead, higher losses are registered, with an average of 3.8%, with quartiles between 35.5% and 36.3%.

Scenarios B1 and B2 are strongly penalised, with losses respectively of 73% and 77%, higher of 39% and 69% of the respective scenarios without adaptation actions.

Of course, the economic results will be very different if certain changes in DOCG regulations and in the market would take place (i.e. allowing permanent irrigation), but this study is not taking this possibility into consideration.

In order to assess the possibility of the farms to keep satisfying levels of income in the different scenarios, it is important to remind that the calculation of TEI includes only the vineyard production phase: even the higher values of TEI have a relative weight if DOCG production is not stopped as they are compensated by the high commercial value of Brunello wines. In this case, though, it is highly probable that the decrease in the production levels require a reorganisation of the filière, with a higher concentration of the grapes produced in the area in a lower number of cellars. As selling grapes is not convenient, in order to prevent a heavy loss for the growers, it might be appropriate to support association initiatives.

The most important result, however, is that, considering the high average quality level of the productions of the area, farms tend to respond to climate change without stopping DOCG wine production, even accepting high

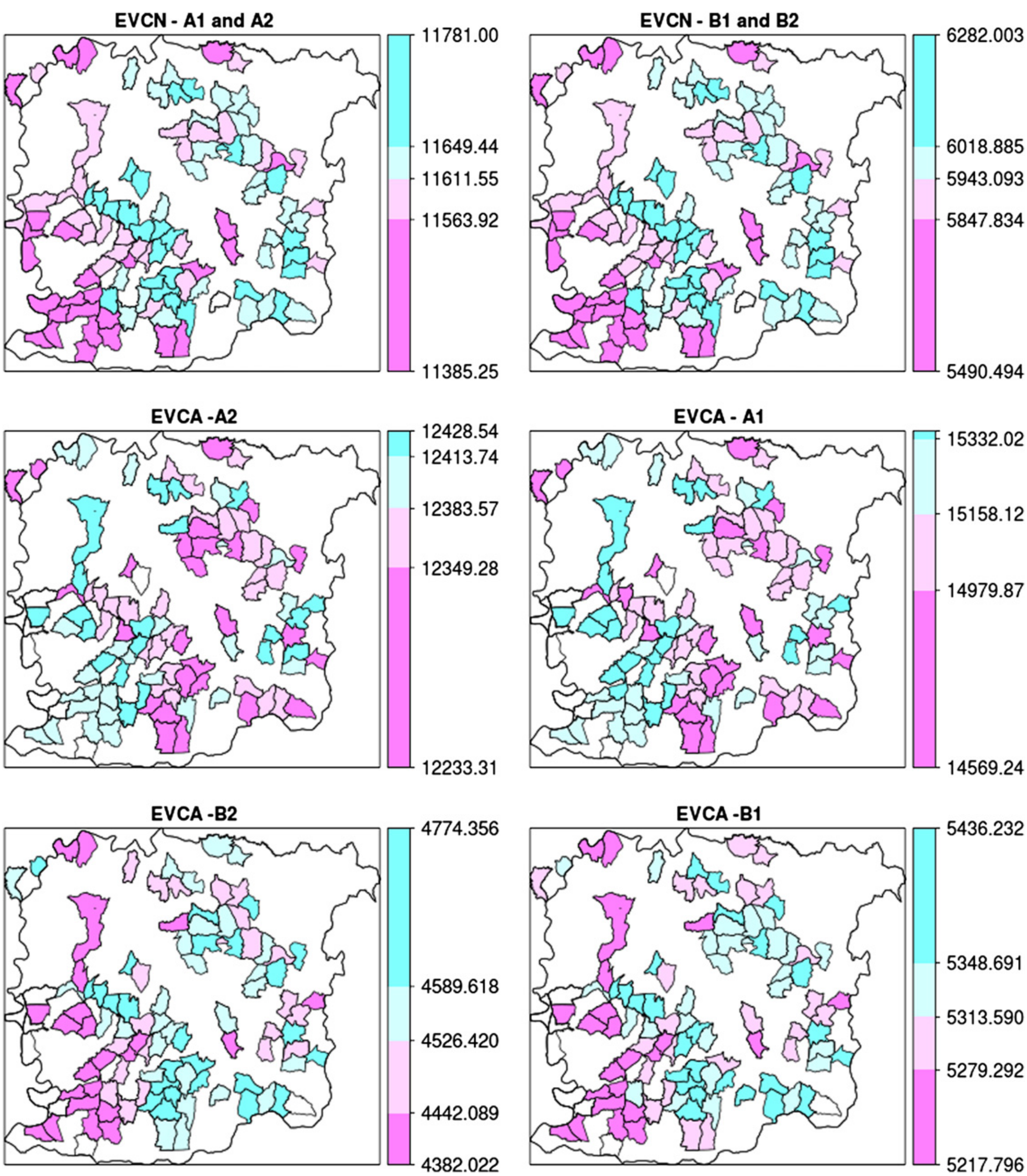


Fig. 12. Economic results for the analysed scenarios.

losses, adapting the cultivation techniques to these changes and accepting lower productivity per hectare.

## 5. Conclusions

This study has shown that expected damage from climate change will have substantial effects that justify adoption of adaptation measures, even very expensive ones, to preserve the quality and identity of Tuscan viticulture. This study has sought to assess whether and how such measures would allow for the cultivation of a product that is compatible with current quality standards. Obviously, it is necessary to assess the impact of land changes and production techniques on the total costs of wine making, with consequences for the repositioning of products in different price ranges in relation to specific targets, direct competitors and levels of customer satisfaction. The collected data and the simulations carried out with the model confirm that farms do not benefit from stopping the production of DOCG wine to start producing IGTs: this suggests a few modifications for the future, first of all in the regulations about irrigation, carefully valuing the consequences on product quality on a production and consumer perception level.

This finding, even in the case of changes in the DOCG regulations, suggests the need to establish adequate public policies to support local production, taking into account the consequences that weakening of the wine production system could have not only on the primary sector but also on the entire local socioeconomic system (especially on the landscape and tourism). This is an issue common to all areas where there is wine production in Italy, where vine cultivation and wine production are associated with forms of high district intensity in the sector.

The proposed model represents a first implementation of an innovative methodology that requires further improvements at both the theoretical and methodological levels, with validation on a wider case study spectrum. In particular, the model could be improved by considering the effects of adaptation measures on the competitiveness of the products in the market, with special attention not only to direct and indirect costs but also to variations in the quality of wines in relation to the expectations of consumers. Climatic and eco-soil variables related to the vulnerability of the *terroir* will also have to be verified and possibly expanded, along with socioeconomic ones related to the farms. Lastly, the model needs to be applied to wider areas, using the latest census data, as soon as they are available.

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