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Alisa Spiegel[1], Simone Severini[2], Wolfgang Britz[3], Attilio Coletta[2]*

[1] Business Economics Group, Wageningen University, the Netherlands
[2] Department DAFNE, Università della Tuscia, Italy
[3] Institute for Food and Resource Economics, Bonn University, Germany

** Corresponding author: alisa.spiegel@wur.nl*

Editor: Thomas Heckelei

Institute for Food and Resource Economics

University of Bonn

Nußallee 21

53115 Bonn, Germany

Phone: +49-228-732332

Fax: +49-228-734693

E-mail: thomas.heckelei@ilr.uni-bonn.de

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[3] Institute for Food and Resource Economics, Bonn University, Germany

* *Corresponding author: alisa.spiegel@wur.nl*

Abstract

Recent literature reviews of empirical models for long-term investment analysis in agriculture see gaps with regard to (i) separating investment and financing decisions, and (ii) explicit consideration of associated risk and temporal flexibility and (iii) taking farm-level resource endowments and other constraints into account. Inspired by real options approaches, this paper therefore develops step-wise a model which extend a simple net present value calculation to a farm-scale simulation model which considers time flexibility, different financing options and downside risk aversion. We assess the different model variants empirically by analyzing investments into hazelnut orchards in Italy outside of traditional producing regions. The variants return quite different optimal results with respect to scale and timing of the investment, its financing and expected NPV. The step-wise approach reveals which aspects drive these differences and underlines that considering temporal flexibility, different of financing options and riskiness can considerably improve traditional NPV analysis.

Keywords: Perennial crop; real options; stochastic dynamic modelling; stochastic optimization.
JEL classification: C61, G11, Q12, Q14, Q15

1 Introduction

Recent literature reviews on empirical models for long-term investment analysis see gaps with regard to separating investment and financing decisions (e.g., Trigeorgis and Tsekrekos, 2018) and explicit consideration of associated risk and temporal flexibility (e.g., Shresta et al., 2016). Furthermore, opportunity costs, farm-level resource endowments, multiple risk sources and risk preferences are also rarely taken into account. This paper illustrates how to include all these aspects into farm-level investment analysis and highlights resulting differences based on an empirical example of investing into hazelnut trees.

Shresta et al. (2016) find that the classical investment theory, which maximizes the net present value (NPV), or alternatively optimizes the internal rate of return (IRR), or the pay-off period, remains the most frequently applied one (e.g., Schweier and Becker, 2013; Bett and Ayieko, 2017). The two major limitations of doing so are well known (among others see Freixa et al., 2011; Robinson et al., 2013; Badiu et al., 2015; Sgroi et al., 2015; Stillitano et al., 2016). First, the underlying risk of the investment project is not explicitly represented and instead reflected by increasing the discount rate above market levels. Other parameters enter with their expected values, neglecting probability both underlying riskiness and potential correlation between parameters. Second, the classical investment theory depicts a "now exactly as defined or never" decision problem where neither future adjustment to the investment project under changed environment nor its postponement are considered. This easily leads to overestimation of investment triggers (Wolbert-Haverkamp and Musshoff, 2014). The new investment theory aims to overcome these limitations. In particular, the application of the real options approach to agricultural investment projects has gained interest (e.g., Wossink and Gardebroek 2006; Hinrichs et al 2008; Maart-Noelck and Musshoff 2013; Spiegel et al 2020), although empirical application is still limited, e.g., in the domain of perennial crops. While quantitative analysis of investments into perennial crops has a long history (e.g., Jackson 1985), it mainly sticks to the classical investment theory. Despite considerable market and production risk in orchard production, only a few more recent studies, such as Sojkova and Adamickova (2011), consider risk. Not astonishingly, they find substantial differences in optimal investment levels compared to NPV calculations. That suggests that deterministic models may provide flawed estimation of investment dynamics and scale. As for optimal financing behavior, many studies investigate with other methods different aspects and determinants of farm-level demand for credits, such as present risk management strategies (Katchova, 2005), credit source (Farley and Ellinger, 2007), interest rate (Turvey at al., 2012; Fecke et al., 2016), farmer's personal characteristics and farm structural variables (Howley and Dillon, 2012). While financing behavior is found to affect farm performance, financial risk, and resilience, its link to investment behavior is still understudied.

Building on this literature, we develop models for valuing and analyzing long-term investment decision on farm, starting with a simple net present value calculation. We expand this model step-wise to a final dynamic stochastic farm-scale simulation model inspired by real options approaches which considers different financing options and down-side risk aversion in the form of minimum household withdrawals. Accordingly, the objectives of the paper are twofold. First, we aim to illustrate how additional investment drivers can be step-wise incorporated, and second, we aim to demonstrate sensitivity of results differ across model variants to underline their relevance. The novelty of our final model is threefold. First, we explicitly consider factors that are still widely ignored when modelling farm-level investment decision, namely temporal flexibility, flexibility in terms of financing options, and the of the farm household. Second, we step-wise introduce these factors into the model to quantify their impact on optimal scale and timing of investments. Finally, we apply the model to a domain where advanced quantitative assessments are lacking, i.e. perennial crops.

We therefore present an empirical application to hazelnut production. This is an interesting study case as it requires long-lasting expensive investments, in form of a plantation, specialized machinery and irrigation. The different models are all set up for the same case study farm located in Viterbo, a central Italian region, where hazelnut production becomes increasingly a quite important agricultural activity. The farm is assumed to currently manage rainfed annual crops, only, and by its size and farm program, is quite representative for farms in that region which are investing into new hazelnut plantations. We explicitly quantify considerable market (Pelagalli, 2018), weather, and other production risks affecting product quality and quantity.

Taking hazelnut production in this region as an example is motivated by further facts. Firstly, with 13% of global hazelnut production, Italy is the second largest global producer after Turkey with ca. 65% (FAO, 2019). International demand for hazelnut and derived products increased over the last decades and is projected to expand further. This triggers new investments in different producing countries, partially initiated by international food industry companies of which one major one is located nearby our study region. In Italy, further expansion of hazelnut orchards in the traditional production districts under rainfed systems is not possible. New plantations are now set-up in surrounding lower areas where irrigation is necessary to ensure relatively stable production and quality levels. In the last three years (2016-2019) the Italian National Institute for Statistics (ISTAT) recorded an increase in the total area devoted to hazelnut cultivations close to 15%. New investments are likely in coming years, according as major companies involved in hazelnut-based food production promote new investments to reach 90.000 hectares of cultivation in Italy solely. The trend of investing into hazelnuts as an alternative land use option also reflects decreased profitability of so far dominating annual crops such as grains and oilseed. Both socio-economic and environmental consequences of this on-going land use change are lively debated (Boubaker et al. 2014, UTZ 2016). So far, economic assessments of investments into hazelnuts at farm level draw on data from specialized producers in the traditional districts, only. Several authors therefore stress the need to better evaluate investments in new producing regions (Bobic et al. 2016, Pirazzoli and Palmieri 2017, Frascarelli 2017).

The paper is organized as follows. Section 2 develops four models step-by-step where each one expands the previous one by relaxing some assumptions to further improve the analysis. Section 3 introduces data and assumptions used in our case study which also show the additional data required for the model expansions. Section 4 presents main empirical results to highlight result differences across the model results. Section 5 concludes with a discussion of pros and cons of the different models and provides suggestions for improvements in the assessment of returns from farm investments.

2 Building-up a stochastic dynamic farm-level model

2.1 *Farm-level endowments, economy-of-scale and alternative crop (ClassNPV)*

We start with simulating discounted cash flows at farm level for either investing now or never – the still dominant approach in literature. In the case of hazelnuts, the nominal cash flows in each year depend on the age of the plantation (Fig.1).

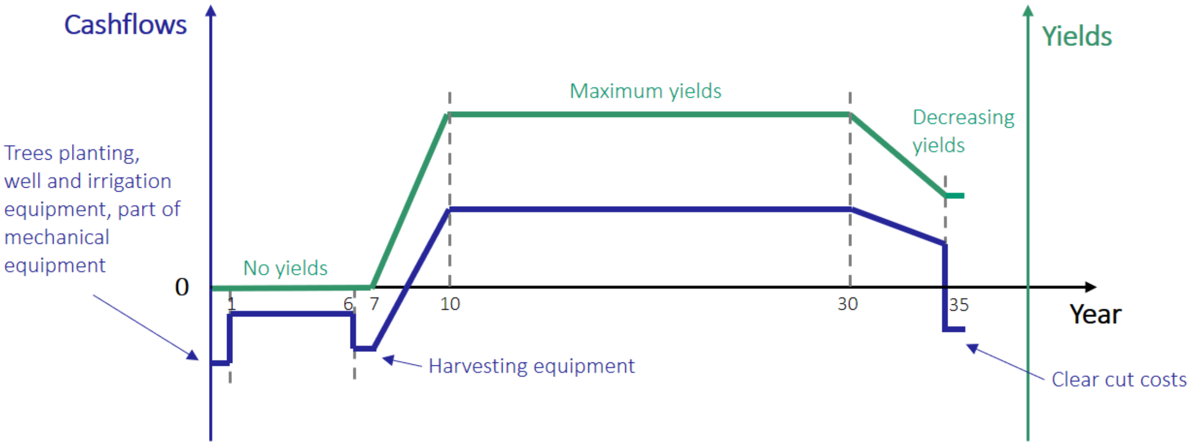

Figure 1: Description of the evolution of a new hazelnut orchard over time.

Source: Own elaboration based on Liso et al (2017) and Frascarelli (2017).

A newly set-up hazelnut orchard can be first harvested in its seventh year. From there to the tenth year, yields increase linearly from zero to a maximum yield level ($maxYields$) which is maintained until the trees are thirty years old. Afterwards, there is a linear decrease in annual yields to 50% of the maximum up to the year 35. The resulting formula for the yield in year *y* is:

$$yield_{hazel,y} = \begin{cases} 0 \quad \forall y \leq 6 \\ 0.2 * (y-6) * maxYields \quad \forall\, 6 < y \leq 10 \\ maxYields \quad \forall\, 10 < y \leq 30 \\ 0.1 * (40-y) * maxYields \quad \forall\, 30 < y \leq 35 \end{cases} \tag{1}$$

where y depicts the year after the initial set-up and thus the age of the plantation; $yield_{hazel,y}$ the hazelnut yields at age y in [tons per hectare [t ha^{-1}]; $maxYields$ stays for the maximum hazelnut yield [[t ha^{-1}]]. Multiplying hazelnut yields with their price and deducting variable costs defines the gross margin per hectare. We capture the difference between the farm-gate and the average regional market price $marketPrice$ by so-called quality index qi, which reflects specific quality of hazelnuts, farmer's negotiation power, and other related factors. Both the quality index and the market price are assumed to be stochastic and represented in the NPV calculation by their expectations. We also distinguish between harvesting costs $harvCost$ per ton harvested, and other costs $otherCost$ per hectare, which include irrigation and fertilization costs. At each age of the plantation y, the cash flow per hectare equal to the gross margin is thus defined as:

$$\begin{aligned} E[gm_{hazel,y}] = yield_{hazel,y} * E[qi_{hazel,y}] \\ * E[marketPrice_{hazel,y}] - yield_{hazel,y} \\ * harvCost - otherCost \quad \forall y \leq 35 \end{aligned} \tag{2}$$

where $E[\cdot]$ is the expectation operator; $gm_{hazel,y}$ stays for the gross margin of hazelnuts [€ ha^{-1}]; $qi_{hazel,y}$ stays for the hazelnuts quality index, which ranges from 0 to 1; $marketPrice_{hazel,y}$ stays for the average market price of hazelnuts [€ t^{-1}]; $harvCost$ stays for the variable harvesting costs [€ t^{-1}]; $otherCost$ stays for the other quasi-fixed costs related to hazelnut cultivation, including irrigation and fertilization costs [€ ha^{-1}]. Furthermore, we consider two (quasi-)fixed resources endowments: land and labor. Additional demand for labor can be satisfied via hired labor. The farm resources are distributed between hazelnuts and durum wheat – an alternative crop to hazelnuts. The acreages of hazelnut and durum wheat can jointly not exceed the given endowment:

$$area_{hazel} + area_{wheat} \leq end_{land} \tag{3}$$

where $area_{hazel}$ depicts land under hazelnuts [ha] and $area_{wheat}$ stays for land devoted to durum wheat [ha]; end_{land} stays for the total fixed and given land endowment [ha]. Labor requirement for the crops are expressed per hectare; for hazelnuts, additional labor hours per harvested tons are needed. Total labor requirement can be covered by on-farm or hired labor:

$$\begin{aligned} area_{wheat} * \overline{lab_{wheat}} + area_{hazel} * \overline{lab_{hazel}} + area_{hazel} \\ * yield_{hazel,y} * \overline{lab_{hm}} \\ \leq end_{lab} + hiredLab_y \quad \forall y \end{aligned} \tag{4}$$

where $\overline{lab_{wheat}}$ stays for labour requirements for durum wheat [hours per hectare, h ha^{-1}]; $\overline{lab_{hazel}}$ stays for quasi-fixed (i.e., independent of yields) labour requirements for hazelnuts [h ha^{-1}]; $\overline{lab_{hm}}$ stays for variable labour requirements for hazelnuts [hours per ton, h t^{-1}]; end_{lab} stays for on-farm labour endowment [hours, [h]; $hiredLab_y$ stays for additionally required labour that can be hired [[h]]. The gross margin of the alternative crop is defined in a similar way as the one of hazelnuts: we specify expected market price, quality index and variable costs:

$$\begin{aligned} E[gm_{wheat}] = E[yield_{wheat}] * E[qi_{wheat}] \\ * E[MarketPrice_{wheat}] - E[cost_{wheat}] \end{aligned} \tag{5}$$

where gm_{wheat} stays for gross margin of durum wheat [€ ha^{-1}]; $yield_{wheat}$ stays for yields of durum wheat [t ha^{-1}]; qi_{wheat} stays for quality index of durum wheat, which ranges from 0 to 1;

$marketPrice_{wheat}$ stays for the average market price of durum wheat [€ t^{-1}]; $cost_{wheat}$ stays for quasi-fixed costs for durum wheat [€ ha^{-1}]. While durum wheat is rain-fed, hazelnuts require irrigation water, such that farmers have to invest into a well and irrigation equipment in addition to the establishment costs of the plantation (Fig.1). Furthermore, harvesting machinery for hazelnuts must be available prior to the first harvesting of hazelnuts. Harvesting machinery is physically depreciated while other machinery is depreciated by lifetime. The formula for NPV then becomes:

$$\begin{aligned} &E[NPV] = \\ &= \left(-iniCost + \sum_{y} \frac{E\left[gm_{hazel,y}\right]}{(1+dr)^{y}} - \frac{reconvCost}{(1+dr)^{35}} \right) * area_{hazel} \\ &+ \\ &+ area_{wheat} * E[gm_{wheat}] - \\ &- invCostWell \\ &- \sum_{y} \frac{\sum_{m} invCostMach_{m,y} + hiredLab_{y} * wage}{(1+dr)^{y}} \end{aligned} \qquad (6)$$

where NPV stays for the net present value over the overall planning horizon $\sum_{y}$ [€]; $iniCost$ stays for the costs associated with initial establishment of hazelnut plantation [€ ha^{-1}]; dr stays for the discount rate [%]; $reconvCost$ stays for the costs associated with final clear-cut of hazelnut plantation [€ ha^{-1}]; $invCostWell$ stays for costs of well and irrigation equipment for hazelnut [€]; $invCostMach_{m,y}$ stays for investment costs for machinery m [€]; $wage$ stays for costs of hired labor [€ h^{-1}]. We optimize the farm-level NPV under endowment constraints by solving for the following decision variables: area of hazelnuts, area of durum wheat and investments into machinery m at each age of the plantation y.

The model advances in accounting for all the required investments as well as resource endowments. It also captures the associated economy-of-scale; in our example, via lifetime and capacities of machines and via fixed costs for a well and irrigation equipment. In another case study, the gross margin of the alternative land use option could also represent average returns from a portfolio of alternative crops instead of one crop, only, as in here durum wheat. As the result, we simulate the maximum possible farm-level NPV under given conditions and constraints. Yet, the model still suffers from limitations. First, it operates with expectations of all stochastic variables, ignoring their underlying riskiness when maximizing the NPV. Second, it implies investing into hazelnuts now or never. Yet, in the case of uncertainty and high sunk costs of an investment project, investors might prefer to wait for new information before making a decision. Here, sunk costs relate to setting up the plantation and investments into a well, irrigation equipment and specialized machines while future prices, yields, and costs are uncertain – and the first yield is generated only seven years after the investment. These circumstances might create an additional value of waiting and of getting more information, such as on price developments for hazelnut. This motivates using the real options instead of a classical NPV approach.

2.2 *Risk and flexibility in timing (RealOpt)*

Spiegel et al. (2018; 2020) demonstrate the advantages of stochastic-dynamic programming for farm-level investment analysis, since it allows considering (quasi-fixed) assets, such as land and on-farm labor, risks, as well as both time and scale flexibility as elements of a real-options approach. They overcome the curse of dimensionality found in binary lattices or similar scenario tree approaches by employing a scenario tree reduction technique (*ibid*.). Building on their work, we transform the *ClassNPV* model developed in the section above into a stochastic-dynamic farm-level model. In contrast to Spiegel et al. (2018; 2020), we consider a second replantation period in order to expand the finite planning horizon so far in the future that differences to the infinite one become marginal from the numerical perspective.

We assume the following aspects of management flexibility. During the first five years the farmer can decide to introduce hazelnut or to continue cultivating durum wheat as an alternative annual crop (*time flexibility 1*). After reaching an age between thirty-two and thirty-five years, the hazelnut trees must be removed; afterwards the land can be either planted again with new hazelnut trees or cropped with durum wheat (*time flexibility 2*). The subsequent plantation must be closed down again after thirty-two to thirty-five years (*time flexibility 3*). This results in a finite planning horizon of seventy-five years such that differences between an infinite and this finite planning horizon should be negligible for any reasonable private discount rate. In order to increase computational speed, we divide the total land endowment into distinct plots of sizes 2^n with $n = 0, 1, 2 \ldots$, which in combination allow any integer plantation size between 0 and the maximal farm land (*scale flexibility*). Using fixed plot sizes instead of a continuous fractional plantation size allows opting for a mixed integer program instead of a mixed non-linear integer program. Integers are needed anyhow to capture indivisibilities in investment (well, machinery). The time flexibility is separately considered for each plot.

Differences compared to the previous model are threefold. First, we consider now the market price and quality index of hazelnuts and durum wheat to be stochastic, as well as yields and variable costs of durum wheat and the wage rate for hired labor. The expected values of all these variables are replaced by probability distributions or stochastic processes, represented by a scenario tree. Each node of the tree contains a vector of stochastic variables' realizations. In this tree, es. Accordingly, in the expanded model, the stochastic variables carry now both time and node indices. Second, we now distinguish between the time period and age of the plantation. In the previous simpler model, hazelnuts could only be planted in the first year such that the plantation's age was equal to the year. Due to the time flexibility in *RealOpt* model, time and plantation age become two different dimensions as the time flies regardless of the farmer's decision when to introduce hazelnuts or not at all. Finally, a plantation now can consist of multiple plots of different age. The farm's operating income is thus defined as follows:

$$\begin{aligned} operInc_{farm,t,n} \\ &= ha_{wheat,t,n} * gm_{wheat,t,n} \\ &- \sum_{p} ha_{hazel,p,t,n} * size_{p} * gm_{hazel,p,t,n} \\ &- \sum_{p} ini_{p,t,n} * iniCost * size_{p} \\ &- \sum_{p} reconv_{p,t,n} * reconvCost * size_{p} \\ &- invWell_{t,n} * invCostWell \\ &- \sum_{m} invMach_{m,t,n} * invCostMach_{m} \\ &- hiredLab_{t,n} * wage_{t,n} \quad \forall t,n \end{aligned} \tag{7}$$

where $operInc_{farm,t,n}$ stays for farm's operating income in time period t and node of the scenario tree n [€]; $ha_{hazel,p,t,n}$ stays for a binary variable of devoting a plot p into hazelnuts in time period t and node of the scenario tree n (1 = the plot is cultivated with hazelnuts; 0 = otherwise); $size_p$ stays for the size of the plot p [ha]; $ini_{p,t,n}$ stays for a binary variable of exercising initial establishment of hazelnuts plantation onto a plot p in time period t and node of the scenario tree n (1 = hazelnuts are introduced; 0 = otherwise); $reconv_{p,t,n}$ stays for a binary variable of exercising clear-cut of hazelnuts plantation onto a plot p in time period t and node of the scenario tree n (1 = hazelnuts are clear-cut; 0 = otherwise); $invWell_{t,n}$ stays for a binary variable of exercising investments into a well and irrigation equipment in time period t and node of the scenario tree n (1 = investments into a well and irrigation equipment are exercised; 0 = otherwise); $invMach_{m,t,n}$ stays for a binary variable of exercising investments into required machinery m in time period t and node of the scenario tree n (1 = investments into machinery are exercised; 0 = otherwise). The discounted operating income is hence the objective variable to be maximized and defined as follows:

$$NPV = \sum_{t,n} prob_{n} * \frac{operInc_{farm,t,n}}{(1+dr)^{t}} \tag{8}$$

where $prob_n$ stays for the probability of the node n to occur [percentage points]. At each node of the constructed scenario tree, the model takes into account available time and scale flexibility, the state of the stochastic variables, as well as resources endowments, and provides the following output:

- Land distribution between hazelnuts and durum wheat. Observing changes in land distribution between different nodes of the tree, one can derive (re)planting decision, as well as decision to expand or clear-cut hazelnut plantation;
- Investments into a well and harvesting and other machinery for hazelnuts, the latter differentiated by size;
- Related economic variables such as costs and revenues.

Although the *RealOpt* model is fairly complex and close to the reality, it has two major drawbacks. Firstly, due to high costs related to the initial investments, the farmer will face considerable negative cash flows during the first years after a plantation is set up. The related costs for financing are most probably underestimated by the average discount rate in the model. Secondly, the model neglects downside risk aversion, while the production cycle of hazelnuts implies significant negative cash flows in several time periods (and related costs). We address both drawbacks stepwise in the two final models.

2.3 *Costs of financing (RealOptFin)*

The *RealOptFin* model introduces a current account of the farm operation. It serves as the source to cover variable and investment costs and receives subsidies and the operating income from selling products. In order to finance investments beyond accumulated cash, the model considers different types of loans with fixed repayment times and interest rates. The benefit for the farmer from the farm operation is represented now by yearly profit withdrawals from the current account of the farm, discounted by his private discount rate. Accordingly, the discount rate now does not longer need to reflect the costs of financing. Instead, the market based discount rate is implicit and endogenously determined depending on the financing decisions.

The farmer now optimizes the expected net present value of future profit withdrawals from the farm operation, considering simultaneously investment and financing decisions. Farm operating income $operInc$ enters the current account as follows:

$$\begin{aligned} curAcc_{t,n} = \sum_{n1-n=1} curAcc_{t1,n1} + operInc_{farm,t,n} \\ - withdraw_{t,n} + \sum_{loans} newLoans_{loans,t,n} \\ - \sum_{loans} repaym_{loans,t,n} \\ - \sum_{loans} intpaym_{loans,t,n} \quad \forall t,n \end{aligned} \tag{9}$$

where $curAcc_{t,n}$ stays for the current account in the year t and node n [€]; $withdraw_{t,n}$ stays for annual farm household withdrawals [€]; $newLoans_{loans,t,n}$ stays for the loans acquired in the year t and node n [€]; $repaym_{loans,t,n}$ stays for the debt to-be-paid in the year t and node n [€]; and $intpaym_{loans,t,n}$ stays for the interest to-be-paid in the year t and node n [€]. The household withdrawals are defined for each combination $\{t, n\}$ based on investment and financing decisions. The reader should note here that introducing endogenous financing decisions implies more accurate simulation of cash flows. In particular, if the previous two models might have omitted cash flows independent of investment decisions, e.g., the Common Agricultural Policy (CAP) first pillar premium, they have to be explicitly modelled here, since they affect the required financing. The operating income is hence defined as:

$$\begin{aligned} operInc_{farm,t,n} &= area_{wheat,t,n} * gm_{wheat,t,n} \\ &- \sum_{p} area_{hazel,p,t,n} * size_{p} \\ &* gm_{hazel,p,t,n} \\ &- \sum_{p} ini_{p,t,n} * iniCost * size_{p} \\ &- \sum_{p} reconv_{p,t,n} * reconvCost \\ &* size_{p} - invWell_{t,n} * invCostWell \\ &- \sum_{m} invMach_{m,t,n} * invCostMach_{m} \\ &- hiredLab_{t,n} * wage_{t,n} + end_{land} \\ &* prem \ \forall t, n \end{aligned} \tag{10}$$

where $prem$ stays for the Common Agricultural Policy (CAP) first pillar direct payments [€ ha^{-1}]. The discounted household withdrawals are now the objective variable to be maximized and defined as follows:

$$NPV = \sum_{t,n} prob_{n} * \frac{withdraw_{t,n}}{(1 + dr)^{t}} \tag{11}$$

2.4 *Downside risk aversion (RealOptFinRisk)*

Explicitly considering profit withdrawals allows introducing a lower limit of income from the farm to ensure that the household can survive, such a limit also acts as risk floor. The previous *RealOptFin* model assumes such minimum withdrawals to be zero, i.e. there are combinations of years and node possible where the household will not receive any income from the farm. This is likely to occur especially in the first years after setting up the plantation where high investment costs coincide with zero or low yields of hazelnuts. Our final *RealOptFinRisk* model instead assumes a minimum withdrawal level in each year. It is calculated by multiplying the level of the farm resource endowments with assumed minimum risk-free returns:

$$withdraw_{t,n} \geq end_{lab} * minWage + end_{land} * prem \tag{12}$$

where $minWage$ is a minimum risk-free off-farm wage [€ h^{-1}]. We assume that the farmer would be able to receive at least the premium of the first pillar of CAP as returns to its land, for instance, by renting it out. Financing and deciding on the yearly withdrawals are hence also measures of risk management. While we ensure that the amount of new long-term loans cannot exceed investment costs in a year – assuming that bank will link such loans to a business plan – short-run loan and postponed withdrawals allow flattening the impact of stochastic operational cash flows from the farm on household withdrawals, i.e. income. The reader should note further that we assume that the quality indices, yields and prices of hazelnut and durum wheat are not correlated. Combining arable farming and a hazelnut plantation thus by itself reduces risk due to natural hedging.

We consider a lower limit on yearly household withdrawals as a rather transparent and easy to communicate measure of risk aversion. Changing the limit in sensitivity analysis can help to inform a decision taker on the trade-offs between ensuring a minimum income level under any potential future development and the expected discounted income level. It does not require to explicitly introduce a risk-utility function in the framework above which is another avenue to develop the model further.

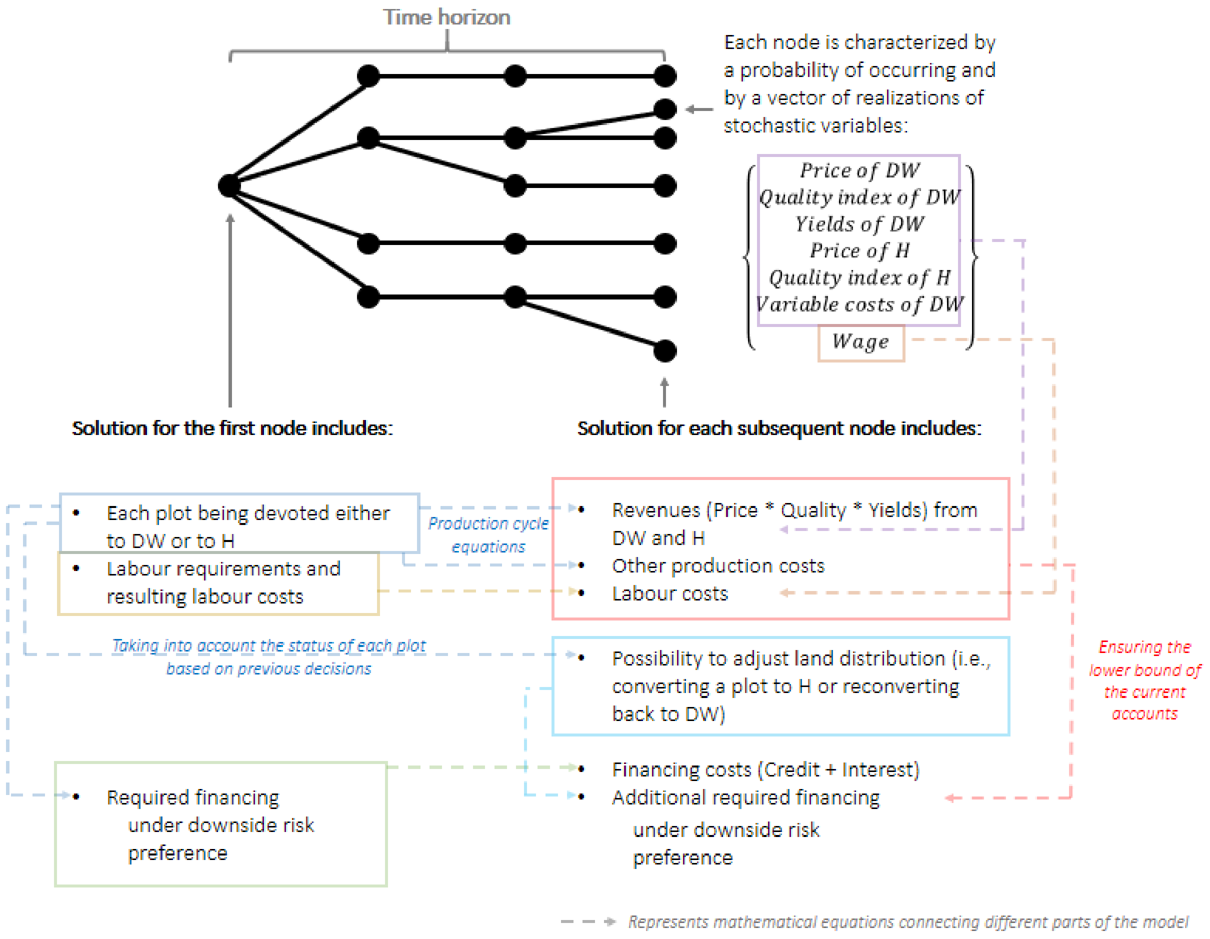

Figure 2. Graphical representation of the *RealOptFinRisk* model's major components and relations between them.

Note: *H stays for hazelnuts; DW stays for durum wheat.*

Figure 2 graphically represents the model and its major components. Each node of the scenario tree contains a vector of realizations of the seven stochastic variables. These realizations enter the calculations of net revenues in each node of the tree which also depend on the set-up and removal decisions with respect to hazelnuts made in this and his ancestor nodes. These decisions translate into the future according to the production cycle and determine required financing, as well as costs of adjusting these production decisions in the future. Financing decisions need to ensure minimum household withdrawals and a non-negative current account. The model simultaneously solves for optimal behavior in all its nodes, maximizing the net present value (Eq. 11) under endowment and other constraints.

2.5 *Comparison of the models*

Fig. 3 below gives an overview on the four models. *ClassNPV* calculates discounted yearly cash flows at farm level under the assumption to convert a part of land into hazelnuts now or never, i.e. it considers scale flexibility under endowment constraints. Consequently, it also considers that additional labor might be needed depending on available farm family labor and the chosen investment program. *RealOpt* adds time flexibility, i.e., it captures and optimizes returns from investment at different time points drawing on a real options approach. That model is next expanded to *RealOptFin* by introducing a difference between the private discount rate, used by the farmer to discount cash flows, and the costs of financing investments, i.e. it also optimizes finance decisions. *RealOptFinRisk* finally ensures that the farming family can withdraw in each year a minimum sum of money from the farming operation. It is also worth to mention that *ClassNPV* does not require a scenario tree as only the expected realizations are needed in each time period. However, the tree realizations can be used post-model to report on the riskiness of the NPV optimized without considering risk.

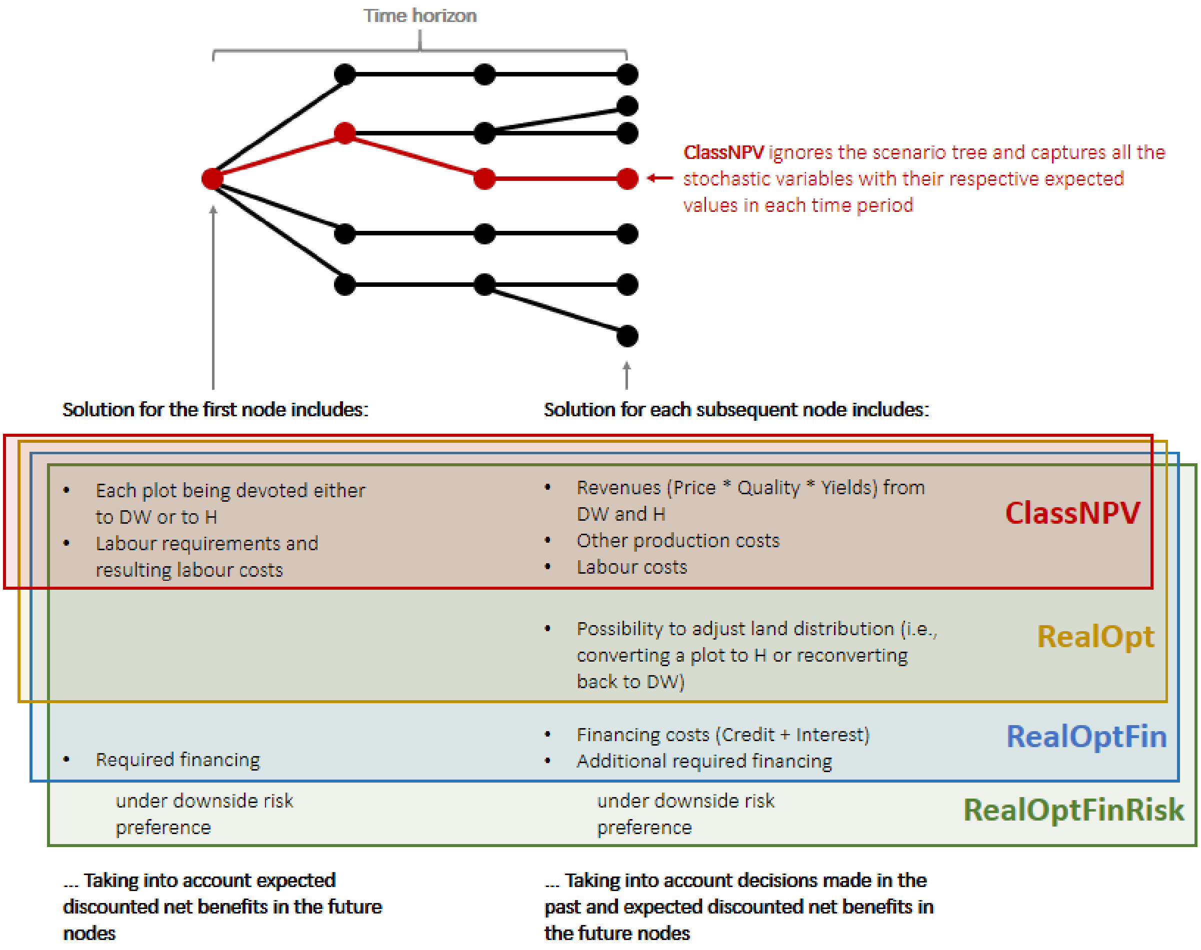

Figure 3. Comparison of components of the four models

2.6 *Solution approach*

We use the solution approach suggested by Spiegel et al. (2018; 2020), which combines Monte-Carlo simulation, scenario tree reduction technique, and stochastic-dynamic programming (Fig. 4). First, 5’000 Monte-Carlo draws are obtained for all the stochastic variables, using empirically predefined stochastic processes and distributions. Jointly this results in a huge scenario tree with 5’000 equally probable independent paths and a realization vector for the seven stochastic variables in each node. This step is done in Java based on standard libraries and own developed code to overcome speed limitations in GAMS. The GAMS-package SCENRED2 by Heitsch and Römisch (2009) reduces the scenario tree in the second step. The underlying scenario reduction technique merges selected paths and nodes and provides new outcomes (i.e., the expected mean of merged outcomes) and the respective probabilities (i.e., the thickness of merged paths). The relation between nodes across time in a scenario tree is captured by an ancestor matrix, generated by SCENRED2. The final step combines the obtained scenario tree with the farm-level model and solves for the optimal investment behavior using stochastic programming. Due to manifold dynamic relations between endogenous variables, all nodes on the same path to a final leave are interrelated. As all paths start with from the same root node, that implies that all nodes need to be simultaneously solved. The code of scenario tree composition and the farm-level model is available online.

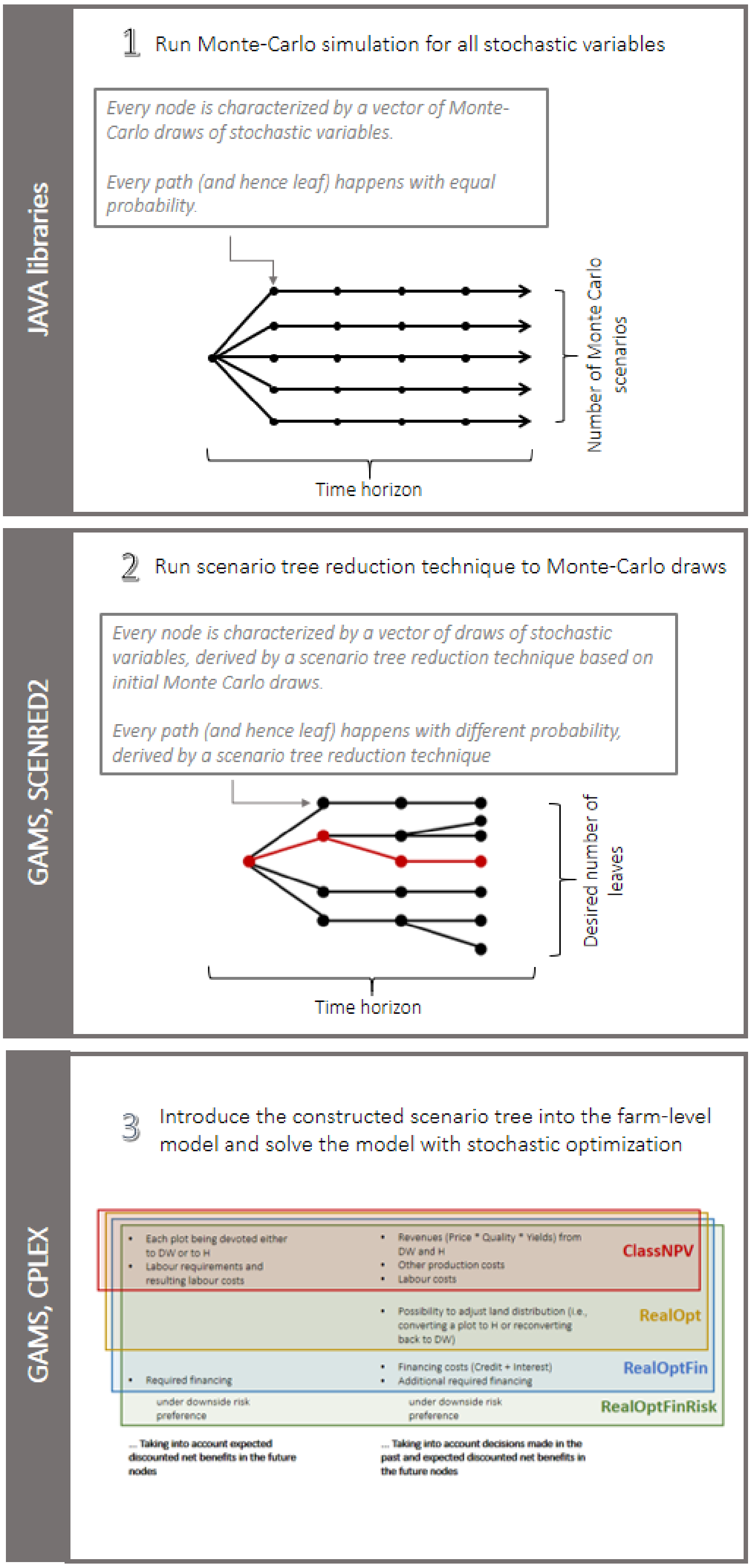

Figure 4. Graphical representation of the solution process.

Source: based on Spiegel et al., 2018; 2020

3 Data and parameters

The parameters of the model draw on multiple data sources, including the Italian Farm Accountancy Data Network (FADN-CREA), Eurostat, World Bank, Census data (ISTAT 2010), agricultural output prices (ISTAT 2018) and the Italian Central Bank, as well as available literature (Frascarelli, 2017; Liso, 2017; Ribaudo, 2011) and expert judgement. The FADN data are only available for the period 2008-2016; the data from ISTAT, Eurostat, and the World Bank were selected for the period 2000-2016. All monetary values were deflated using the GDP deflator for Italy provided by the World Bank (2015=100) to ensure comparability over time.

Traditionally, hazelnut orchards were found in a specific district of the Viterbo province, only, which is specifically suitable for hazelnut cultivation but nowadays doesn’t offer any additional space for new hazelnut cultivation. Therefore, new investments are located in municipalities close by, following a gradient of falling hazelnut yields depending on soil characteristics, climate conditions and often higher irrigation requirements, which mostly depends on the distance to the traditional growing zone. As we focus on new plantations, we only use FADN data related to non-traditional municipalities for hazelnuts, filtered to account for two factors. First, observations referring to years at or close after the establishment of hazelnut plantations were excluded to reflect that no yields occur in the first six years after planting (Frascarelli, 2017). Second, only observations above than 1 ha are included to neglect non-commercial activities in form of “hobby farms”. The regional focus and the two filters led to 62 observations in total. Census data suggest a representative farm size of 30 ha, and, for the considered municipalities, cropping of rain-fed arable crops with durum wheat as the dominant one as the benchmark before considering a hazelnut plantation.

Table 1. Overview of parameters of the four models, their assumed values, and respective references.

Model				Parameter	Value	References
■	■	■	**ClassNPV**	Expected yields of durum wheat	3.9 t ha^{-1}	FADN
				Expected variable costs of durum wheat	371.75 € ha^{-1}	FADN
				Expected market price of durum wheat	237.22 € t^{-1}	Eurostat, Word Bank
				Expected market price of hazelnuts	2,549.66 € t^{-1}	ISTAT, Word Bank
				Expected quality index of durum wheat	0.9247	FADN, ISTAT
				Expected quality index of hazelnuts	0.9817	FADN, ISTAT
				Expected wage of hired labour	10 € h^{-1}	Local collective contracts for hired labour
RealOprFinRisk	**RealOptFin**	**RealOpt**		Available annual labour endowment	350 h	Own elaborations
				Available land endowment	30 ha	FADN
				Hazelnut establishment costs	8,000 € ha^{-1}	Liso et al. 2017, Ribaudo F., 2011, Frascarelli A., 2017
				Investments for a smaller harvesting machinery	8,000 €	Liso et al. 2017, Ribaudo F., 2011, Frascarelli A., 2017
				Labour requirements for a smaller harvesting machinery	32 h ha^{-1}	Liso et al. 2017, Ribaudo F., 2011, Frascarelli A., 2017
				Maximum land area that can be harvested per year with a smaller harvesting machinery	5 ha	Liso et al. 2017, Ribaudo F., 2011, Frascarelli A., 2017
				Total endowment for a smaller harvesting machinery		
				In terms of lifetime	12 years	Liso et al. 2017, Ribaudo F., 2011, Frascarelli A., 2017
				In physical terms	2,000 h	Liso et al. 2017, Ribaudo F., 2011, Frascarelli A., 2017
				Investments for a stand-alone harvesting machinery	40,000 €	Liso et al. 2017, Ribaudo F., 2011, Frascarelli A., 2017
				Labour requirements for a stand-alone harvesting machinery	15 h ha^{-1}	Liso et al. 2017, Ribaudo F., 2011, Frascarelli A., 2017
				Maximum land area that can be harvested per year with a smaller harvesting machinery	15 ha	Liso et al. 2017, Ribaudo F., 2011, Frascarelli A., 2017
				Total endowment for a smaller harvesting machinery		
				In terms of lifetime	12 years	Liso et al. 2017, Ribaudo F., 2011, Frascarelli A., 2017
				In physical terms	3,000 h	Liso et al. 2017, Ribaudo F., 2011, Frascarelli A., 2017
				Other labour requirements for hazelnut (excl. labour required for harvesting machines)		
				Age of plantation: below 7 years (without production)	49.5 h ha^{-1}	Expert based information
				Age of plantation: equal to or more than 7 years	89.5 h ha^{-1}	Expert based information
				Variable harvesting costs of hazelnuts	50 € t^{-1}	Ribaudo, 2011
				Other production costs of hazelnuts, incl.	1,700 € ha^{-1}	Expert based information
				Costs of fertilisation and chemical treatments	800 € ha^{-1}	Expert based information
				Operational costs for other machinery (excl. harvesting)	600 € ha^{-1}	Expert based information
				Irrigation costs	300 € ha^{-1}	Expert based information
				Investments into a well	12,000 €	Liso et al. 2017, Ribaudo F., 2011, Frascarelli A., 2017
				Investments into irrigation equipment for hazelnuts	2,000 € ha^{-1}	Liso et al. 2017, Ribaudo F., 2011, Frascarelli A., 2017
				Investments into tractor	20,000 €	Expert based information
				Lifetime of tractor	20 years	Ribaudo F. (2011)
				Investments into operating machinery for hazelnuts	10,000 €	Expert based information
				Lifetime of operating machinery	10 years	Ribaudo F. (2011)
				CAP direct payment	300 € ha^{-1}	Own elaboration

				Annual discount rate	2%	Own elaboration
			■	Laplace distribution for yields of durum wheat		
			■	Mean	3.9120	FADN
			■	Standard deviation	1.1984	FADN
			■	Expected maximum yields of hazelnuts	2.9 t ha^{-1}	FADN
			■	Mean-reverting stochastic process for natural logarithm of market price of durum wheat		
			■	Long-term mean	5.4690	Eurostat, Word Bank
			■	Speed of reversion	3.1053	Eurostat, Word Bank
			■	Standard deviation	0.4808	Eurostat, Word Bank
			■	Starting value	5.4036	Eurostat, Word Bank
			■	Mean-reverting stochastic process for natural logarithm of market price of hazelnuts		
			■	Long-term mean	7.6782	ISTAT, Word Bank
			■	Speed of reversion	0.9219	ISTAT, Word Bank
			■	Standard deviation	0.1933	ISTAT, Word Bank
			■	Starting value	8.0669	ISTAT, Word Bank
			■	Laplace distribution for quality index of durum wheat		
			■	Mean	0.9817	ISTAT
			■	Standard deviation	0.2580	ISTAT
			■	Laplace distribution for quality index of hazelnuts		
			■	Mean	0.9247	ISTAT
			■	Standard deviation	0.2398	ISTAT
			■	Gamma distribution for variable costs of durum wheat		
			■	Shape	3.8286	FADN
			■	Scale	97.098	FADN
			■	Uniform distribution for costs of hired labour		
			■	Minimum	7.50 € h^{-1}	Expert based information
			■	Maximum	12.50 € h^{-1}	Expert based information
		■	■	Annual interest rate for		
		■	■	Short-term credit [1 year]	7%	Own elaboration
		■	■	Middle-term credit [5 years]	6%	Own elaboration
		■	■	Long-term credit [10 years]	5%	Own elaboration
	■	■	■	Minimum off-farm risk-free wage rate	6 € h^{-1}	Expert based information

Table 1 provides an overview of the parameter values and related data sources. For durum wheat and hazelnuts, expected yields are derived from the FADN sample based on total production and area. Since there is no information on the age of the respective plantations, we corrected the resulting average hazelnut yields by a coefficient of 1.25 and assumed it to be the maximum hazelnut yields. That coefficient reflects the average relation between the maximal yield and the yield developments depicted in Eq.(1) above. In order to estimate the expected market prices of unshelled hazelnuts and durum wheat, the market prices in Italy provided by ISTAT (for hazelnuts) and Eurostat (for durum wheat) were used. Furthermore, in order to account for expected future increases in hazelnut price due to increasing global demand, we correct the price derived from historical observations by a multiplicative coefficient of 1.18[1]. For quality indices, the FADN data were used to derive yearly per unit farm specific prices of hazelnuts and durum wheat by dividing crop revenues by sold quantities. These calculated farm-gate prices were normalized by the market prices in Italy provided by ISTAT (2018) for hazelnuts and durum wheat to define samples of farm specific quality indices.

We differentiate two sizes of a specialized harvester for hazelnuts between which the model can chose endogenously. The cheaper harvester is drawn by a tractor ordinarily used for other activities. The more expensive self-driving harvester reduces per ha labor needs and has a longer lifetime measured in harvested area.

Compared with the *ClassNPV* model, the other models require converting expectations of stochastic variables (i.e., quality indices and market prices of hazelnuts and durum wheat, as well as yields and variable costs of durum wheat) into stochastic processes or distributions. All the stochastic variables are mutually independent, i.e. the correlation coefficient between any two stochastic variables is assumed to be zero. In particular, the market prices of hazelnuts and durum wheat are captured by uncorrelated mean-reverting stochastic processes defined as follows:

$$dprH_t = \mu_{hazel}(\theta_{hazel} - prH_t)dt + \sigma_{hazel}dW_t^{hazel} \tag{13}$$

$$dprDW_t = \mu_{wheat}(\theta_{wheat} - prDW_t)dt + \sigma_{wheat}dW_t^{wheat} \tag{14}$$

where t is the time period; $hazel$ indicates hazelnuts; index $wheat$ indicates durum wheat; prH_t is the natural logarithm of hazelnuts price; $prDW_t$ is the natural logarithm of durum wheat price; μ is speed of reversion; θ is long-term logarithmic average level of price; σ is standard deviation; and dW_t^{hazel} is standard Brownian motion independent from dW_t^{wheat}. Other stochastic variables, namely a quality

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[1] This assumption is suggested by the empirics; furthermore, we ran sensitivity analysis with respect to the multiplicator and selected this level, since it leads to different results across the models and hence allows illustrating the effect of increased complexity.

index of hazelnuts and a quality index, yield and variable costs of durum wheat are captured by distributions. More details on deriving the stochastic processes and distributions based on historical data are presented in the Appendix.

4 Results and discussion

We focus in this section on differences between the models with respect to key results: scale and timing of optimal hazelnuts introduction, expected NPV, as well as financing decision (Table 2). In particular, according to the *ClassNPV* model, hazelnuts cannot compete with the representative alternative arable crop durum wheat. Accordingly, the expected NPV of *ClassNPV* (rows 4-5 in Table 2) reflects returns from cultivating durum wheat only and hazelnuts are never introduced. In contrast, a hazelnut plantation might be set-up in later years in the *RealOpt* model which considers temporal flexibility. Specifically, that model suggests that a land share of about 48% of hazelnuts in the second year or later is optimal. This does not imply that in any future stochastic scenario hazelnuts are cultivated. Temporal flexibility means that the farmer can wait, observe how the stochastic environment evolves, and take an investment decision depending on which node of the scenario tree is realized in the future. The 48% are hence an expected share. Row 2 in Table 2 reports the earliest time point where any hazelnuts are introduced (if at all). While both *RealOpt* and *RealOptFin* imply waiting at least for two years before setting up the first time a plantation, *RealOptFinRisk* suggests even longer postponement as the minimal year profit withdrawal is increased from zero in *RealOpt* to opportunity costs reflecting of-farm wages and renting out land. Durum wheat exceeds these opportunity costs in any year and node, but hazelnuts not. Accordingly, the *RealOptFinRisk* model has to postpone investments until hazelnuts are only introduced on such nodes where for these and any subsequent future nodes the minimal income of farming exceeds opportunity costs. For the remainder of the stochastic tree, only durum wheat is cropped. Compared to *RealOpt*, this implies a lower average discounted household income however at reduced downside risk.

Table 2. Comparison of empirical results of different models

		ClassNPV	**RealOpt**	**RealOptFin**	**RealOptFinRisk**
(i)	**Production cycle**	**Yes**	**Yes**	**Yes**	**Yes**
(ii)	**Spatial flexibility**	**Yes**	**Yes**	**Yes**	**Yes**
(iii)	**Economy-of-scale**	**Yes**	**Yes**	**Yes**	**Yes**
(iv)	**Resources endowments**	**Yes**	**Yes**	**Yes**	**Yes**
(v)	**Time flexibility**	**No**	**Yes**	**Yes**	**Yes**
(vi)	**Optimising financing costs**	**No**	**No**	**Yes**	**Yes**
(vii)	**Downside risk preferences**	**No**	**No**	**No**	**Yes**
(1)	Expected area under hazelnuts, % of total farm land endowment	-	48.07	40.80	6.03
(2)	Time period when introducing hazelnuts for the first time	-	$t = 3$ (in 2 years)	$t = 3$ (in 2 years)	$t = 4$ (in 3 years)
(3)	Is earlier reconversion applied?		yes	yes	yes
(4)	Expected NPV at farm-level, €	541,740.32	593,267.05	567,052.33	544,800.89
(5)	Expected NPV per hectare, € *[calculated as (4) divided over the total farm land endowment]*	18,058.01	19,775.57	18,901.74	18,160.03
(6)	Used harvesting machine(s)	-	Large	Large	Large
(7)	Total expected amount of new loans over the planning horizon, €			Short: 110,534.94 Middle: 2,602.33 Long: 1,720,204.63	Short: 140,573.06 Middle: 11,792.54 Long: 432,047.90
(8)	Total expected amount of interest paid, €			481,262.14	130,775.94

The temporal flexibility introduced in *RealOpt* allows increasing the expected NPV by 9.5% compared with the *ClassNPV* model. Note that generally the NPV can never decrease when additional flexibility is considered if all other assumptions are equal. Explicitly considering the costs of financing in *RealOptFin* slightly decreases the competitiveness of hazelnuts and reduces the NPV by 4.4% compared with the *RealOpt* model. That means that the discount rate used in *RealOpt* underestimates the true costs of financing. Yet, considering downside risk aversion in the *RealOptFinRisk* model has an even stronger effect: only around 6% of the total land is converted to hazelnut in the third year or later. The expected NPV drops by 8.2% compared with the *RealOpt* model and by 3.9% compared with the *RealOptFin* model. However, the expected NPV under *RealOptFinRisk* still slightly exceed the one of the *ClassNPV* model by 0.6%.

Fig. 5 compares the riskiness of the resulting NPV in the four models described above and the *forceHazel* model – a model that forces immediate conversion of the whole farm into hazelnuts. The *forceHazel* model considers no financing options, as otherwise it has no feasible solution. The *forceHazel* model is therefore similar to the *classNPV* model except for having no scale flexibility. The models *forceHazel* and *classNPV* hence represent the two corner solutions: the former suggests to distribute all the resources to hazelnuts, the latter – to the alternative crop. Both deterministic models *forceHazel* and *classNPV* ignore any risk and consider any stochastic variable related to both hazelnuts and the alternative crop durum wheat as its expected value. We however recovered the associated riskiness in resulting NPVs by applying the optimal behaviour in both models to the constructed scenario tree (Fig. 5). One can observe that hazelnuts imply much more risk of the resulting NPV, while also leading to a slightly lower expected NPV (compare *forceHazel* and *classNPV* in Fig.5). In contrast, the other three models directly report the riskiness of the NPV and consider it when searching for the optimal investment and financing behaviour. While *realOpt* and *realOptFin* are quite similar in terms of the spread of the NPV, the model *realOptFinRisk* clearly outputs a less risky NPV due to its lower limit on yearly household withdrawals, however as noted already above, at the costs of a lower expected NPV (Fig. 5).

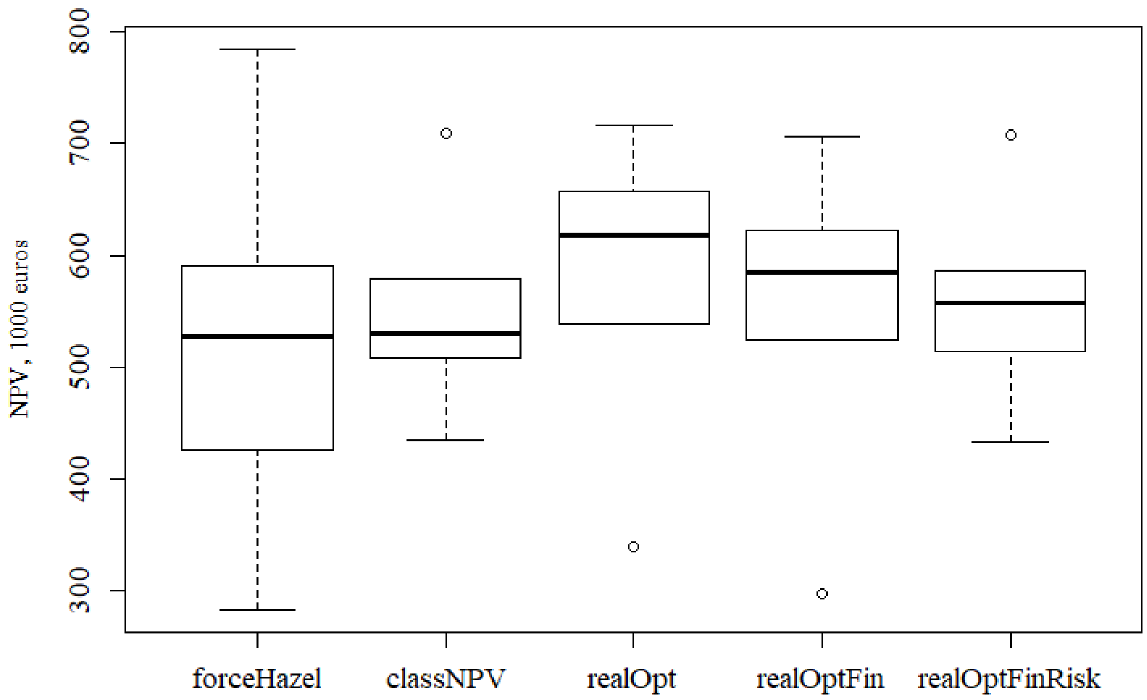

Figure 5. Distributions of maximized net present values in the five models, incl. forceHazel – an additional model that forces immediate conversion of the whole farm into hazelnuts. The *forceHazel* model assumes no financing constraint, as it has no feasible solution otherwise. Both *forceHazel* and *classNPV* models ignore the associated risk and treat all the stochastic variables as their expectations, yet we recovered the riskiness of resulting NPVs based on the optimal behaviour that the models suggest.

Figure 6 visualizes the riskiness of the four models in greater details. *ClassNPV* implies no hazelnuts and reflects the moderate riskiness of durum wheat cultivation, only. The upper panel shows that quite clearly, as the cloud with the points showing the different outcomes for the farm income is quite dense. In contrast, *RealOpt* implies much more risky withdrawals, including considerable positive and negative outliers. Moreover, annual withdrawals implied by *RealOpt* echo the production cycle of hazelnuts: negative withdrawals in the beginning of the time horizon (establishment of the first plantation) and between time periods 35 and 40 (establishment of the second plantation), combined with high positive withdrawals that are associated with periods of maximum yields of the hazelnut plantation.

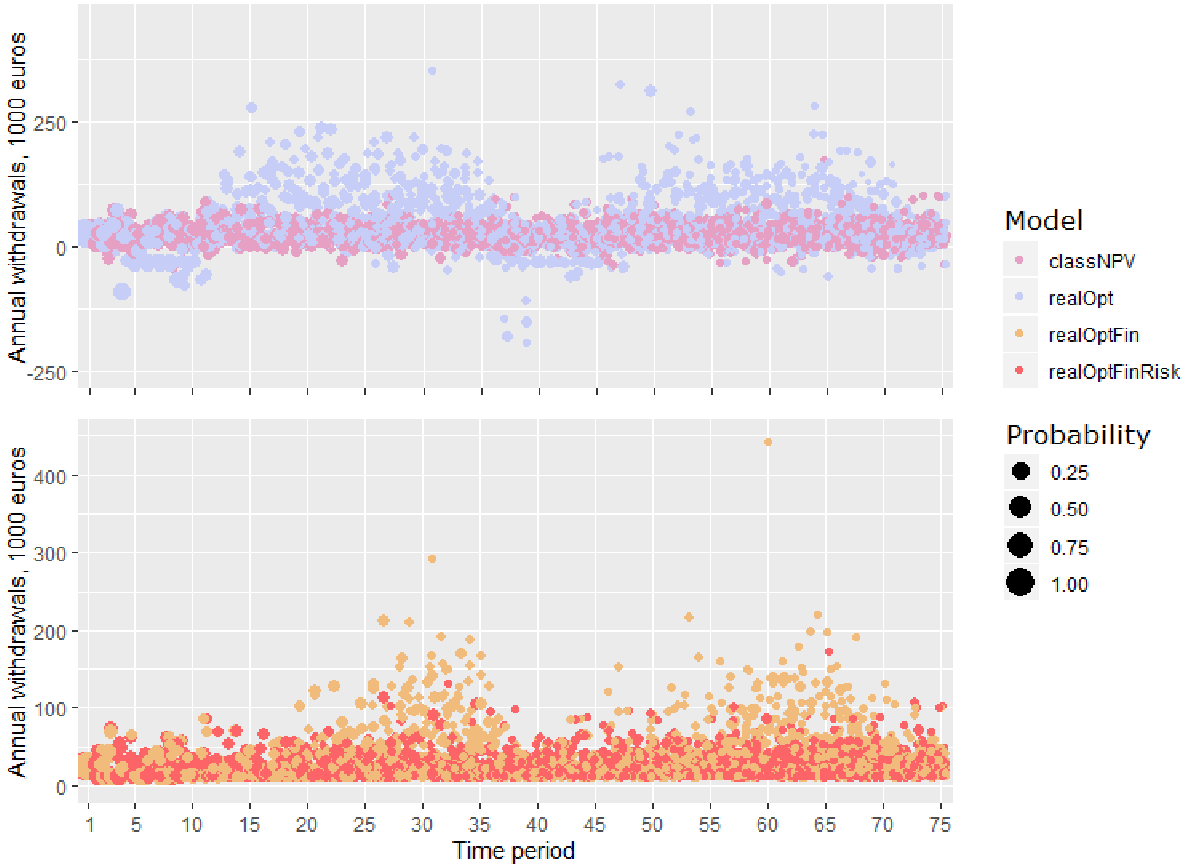

Figure 6. Distributions of annual withdrawals across the planning horizon in the four models

Both models with financing (the lower part of Fig. 6) cut off the negative withdrawals by covering them with short-term credits or by not withdrawing all profits in some years, i.e. using a retained profit position. Without these internal and external financing options, a lower limit of household withdrawals of zero or above in any year under all potentially considered futures cannot be achieved. This is visible from the upper panel as even under the *classNPV* where only durum wheat is grown, there are some years where farm profits become negative.

These last two models differ mainly in financing behaviour. The *RealOptFin* model only needs to maintain a positive current account of the firm but can reduce household withdrawals in certain years down to zero. As a consequence, it uses almost solely long-term credits (Table 2, row (7)) to finance the initial investment costs of plantation set-up and the well, as well in some later years later the first investment in a harvester. The costs relate to an expected 41% land share under hazelnuts (Table 2, row (1)). In contrast, the *RealOptFinRisk* model ensures minimum annual withdrawals above opportunity costs and has to use also short- and especially middle-term credits to balance annual fluctuations in withdrawals (Table 2, row (7)). These reflect foremost the production cycle, i.e. plantation ages of no or low hazelnuts yields, but also relate to nodes in scenario tree with lower than average prices and/or quality indices. Since only 6% compared to 41 % of total land is in the expected mean devoted to hazelnuts, the required investment costs are considerably lower such that the amount of long-term credits decreases substantially compared with the *RealOptFin* model.

5 Discussion and conclusion

Our case study results highlight that the assumptions underlying the different model variants can considerably affect key results. The comparison confirms that more advanced models are more informative: they provide additional insights along with more detailed advice to farmers, such as on how to best finance an investment and how to buffer income fluctuations from production and market risks. The step-by-step development of the advanced farm-level models allows to identify the relative importance of the additional element considered and to illustrate their value added. For instance, the simple NPV calculation suggests not planting hazelnut at all while all the other more complex models suggest doing so, however at varying time periods and scales. Constraining the downside risk of income from the farm operation in the most advanced models not only highlights the trade-off between mean income and reduced down-side risk, but also shows the resulting consequences on the scale and timing of investments.

Clearly, there is a trade-off between additional insights and potentially more realistic results on the one hand and increased data demands (Table 1) and model complexity on the other hand. Additionally, higher data requirements imply typically also higher uncertainty. For instance, the more advanced model with explicit financing costs does not simply require one average interest rate, but interest rates for different finance instruments which depend on a number of factors, such as credit amount or farmer's credit scores. The results – both additional ones and the ones also found in simpler models – are sensitive to what is assumed here in detail on top of the parameter found also in simpler models. Compared to sensitivity to one average discount rate only, the more advanced model distinguishes between different components of discount rate, i.e., time preferences, risk preferences, costs of financing, etc., which all can be subject individually to sensitivity analysis to inform on their importance. Furthermore, such sensitivity analysis could also help to find the set parameters under the considered which best fits the observed (e.g. Troost and Berger 2014). In our case, expected hazelnuts yields and market prices and their riskiness would be obvious first candidates for such an analysis.

As a word of caution, we remind the reader that using more advanced methods such as real options does not necessary imply a better fit to observed behaviour. Indeed, especially the full rationality assumption inherent in optimization approaches might be questioned. A potential promising avenue here is to expose farmers facing investment decisions to results of such models in order to learn more. For instance, how they frame the decision problem including which results matter to them most, or to contrast subjective perceptions of market developments and related risk with findings from statistical analysis. The detailed what, how and when view of dynamic programming approaches might ease that kind of dialogue as it might be similar to the one used by the farmer itself.

Overall, our paper underlines that the conceptual and technical elements are readily available to build farm-scale models based on dynamic stochastic optimization. This allows to determine scale and timing of long-term investments under production and market risk and endowment constraints, drawing on real options. We also highlight that such models are extensions of the widely used farm programming approaches and show the additional insights which can be gained from their application.

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Appendix. Capturing stochastic variables with stochastic processes and distributions based on historical data

A.1 Market price of hazelnuts and durum wheat

In order to estimate the stochastic processes for market prices of unshelled hazelnuts and durum wheat, the market prices in Italy provided by ISTAT (for hazelnuts) and Eurostat (for durum wheat) were used (Fig.A1).

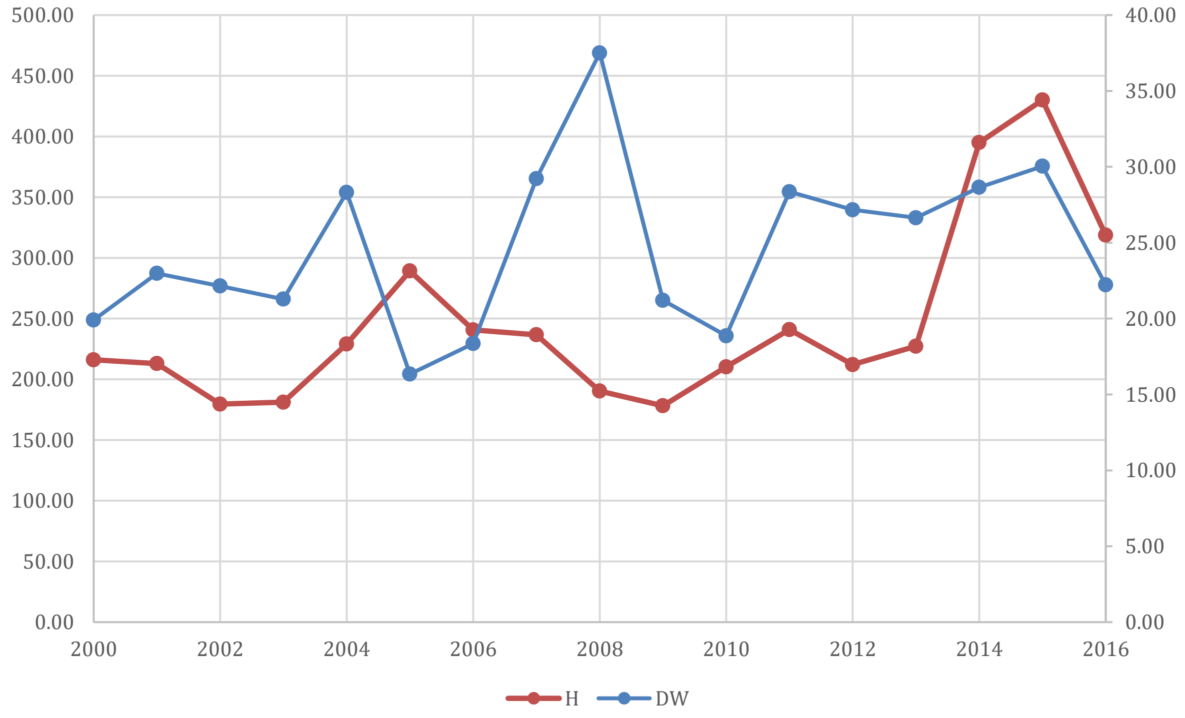

Figure A1. Real durum wheat (DW) and hazelnut (H) prices, € 100kg^{-1}. Source: ISTAT and Eurostat; the prices are deflated (2015=100) using the GDP deflator in Italy provided by the World Bank.

We omit the observations from the years 2008 and 2014-2016 for hazelnuts, as they do not fit the general trend and hence should be excluded when estimating stochastic processes. We ran the following stationarity tests: Augmented Dickey-Fuller (ADF) test; Phillips–Perron (PP) Unit Root test; and Kwiatkowski–Phillips–Schmidt–Shin (KPSS) test. For both data samples, non-stationarity hypothesis cannot be rejected based on the ADF and PP tests, while the KPSS test concludes that stationarity hypothesis cannot be rejected. In light of the conflicting results of these tests, we decide on the appropriate method based on economic reasoning and therefore apply an MRP estimation. This assumes stationarity reflecting that the market price likely fluctuates around a constant long-term per unit production cost under the assumption of no monopolistic power and of constant technology. The result of the MRP estimations are summarized in the Table A1.

Table A1. Estimated parameters of mean-reverting processes for hazelnut and durum wheat prices. Source: own estimation based on the ISTAT (for hazelnuts, years 2000-2013) and Eurostat (for durum wheat, years 2000-2016, excl. 2008) data. The prices were deflated (2015=100) using the GDP deflator for Italy provided by the World Bank.

	Natural logarithm of hazelnut price	**Natural logarithm of durum wheat price**
Long-term mean	7.6782	5.4690
Speed of reversion	0.9219	3.1053
Standard deviation	0.1933	0.4808
Starting value	8.0669	5.4036

Furthermore, as above, we correct every price draw by a multiplicative coefficient of 1.18 in order to account for expected increase in hazelnut price due to increasing demand. This price level also leads to introduction of hazelnut in some but not all model variants and also to highlight differences.

A.2 Quality index for hazelnut and durum wheat

The FADN data were used to derive yearly per unit farm specific prices of hazelnuts and durum wheat by dividing crop revenues by sold quantities. These calculated farm-gate prices were normalized by the market prices in Italy provided by ISTAT for both hazelnuts and durum wheat to define samples of farm specific quality indices. These observations for quality indices were fitted to a Laplace distribution with a mean of 0.9247 and standard deviation of 0.2398 (Fig.A2) for hazelnut, and mean of 0.9817 and standard deviation of 0.2580 (Fig.A3) for durum wheat.

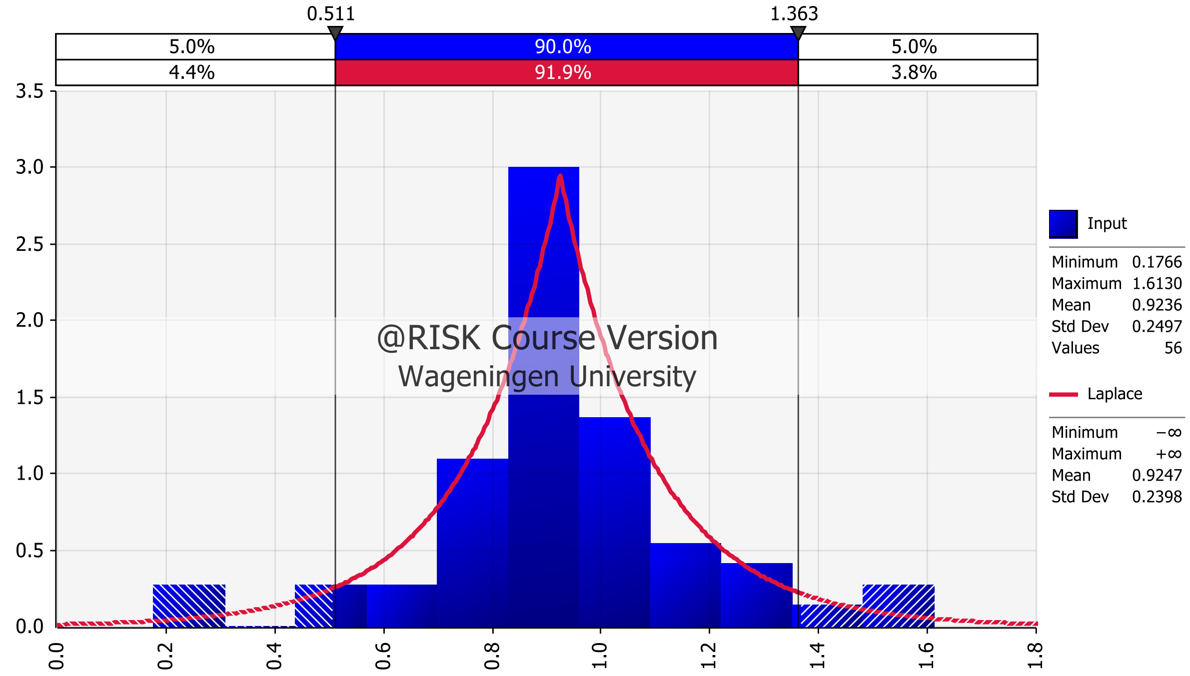

Figure A2. Distribution fitting for the quality index of hazelnut. Source: own elaboration based on FADN and ISTAT data.

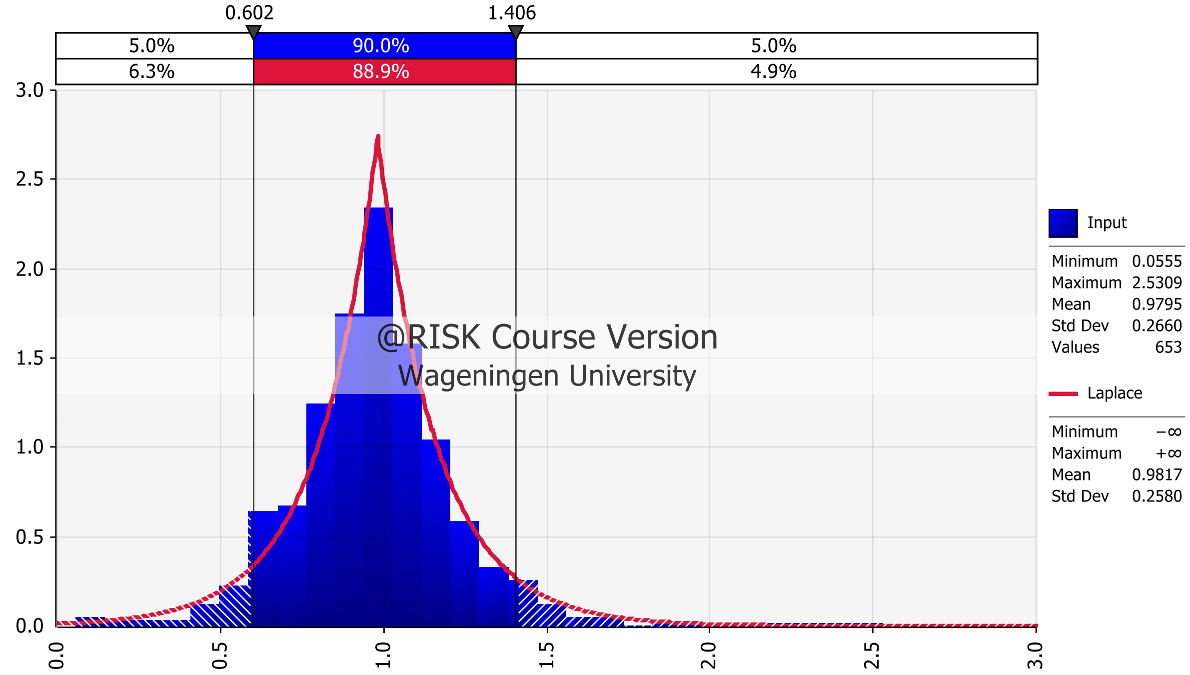

Figure A3. Distribution fitting for the quality index of durum wheat. Source: own elaboration based on FADN and Eurostat data.

A.3 Yields and variable costs for durum wheat

For durum wheat, yields derived from the FADN sample based on total production and area were fitted to a Laplace distribution with a mean of 3.9120 and standard deviation of 1.1984 (Fig.A4). The observations for durum wheat costs were fitted to a Gamma distribution with a shape parameter of 3.8286 and a scale parameter of 97.098 (Fig.A5).

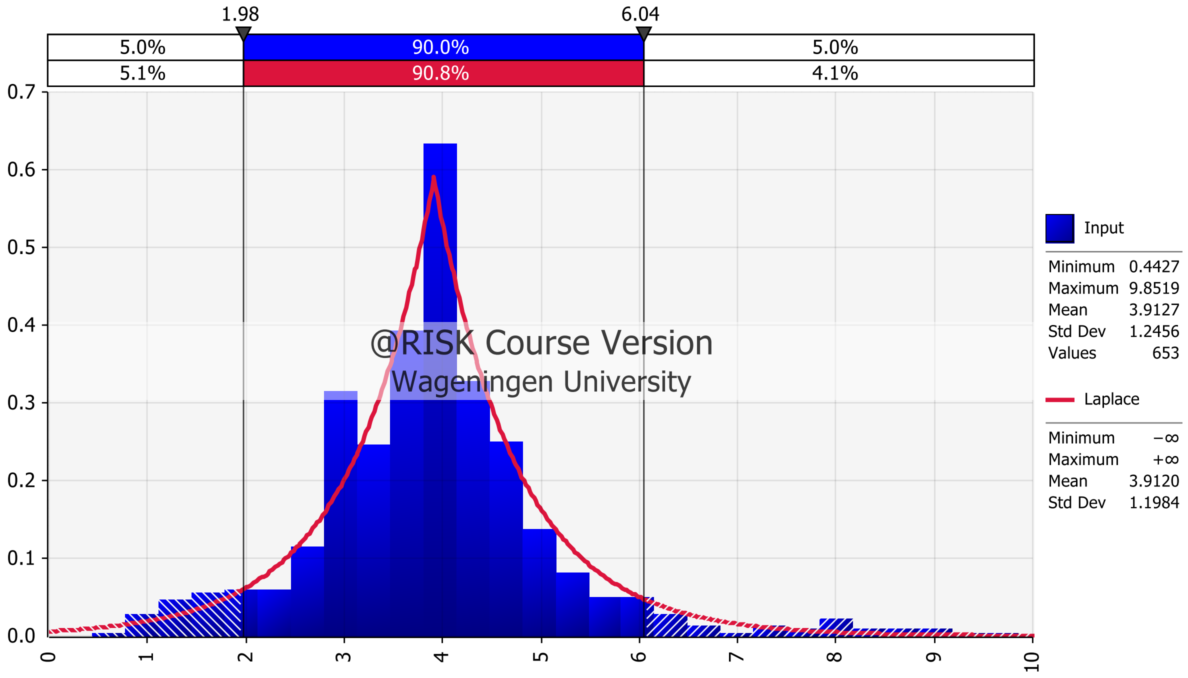

Figure A4. Distribution fitting for the yields of durum wheat. Source: own elaboration based on FADN data.

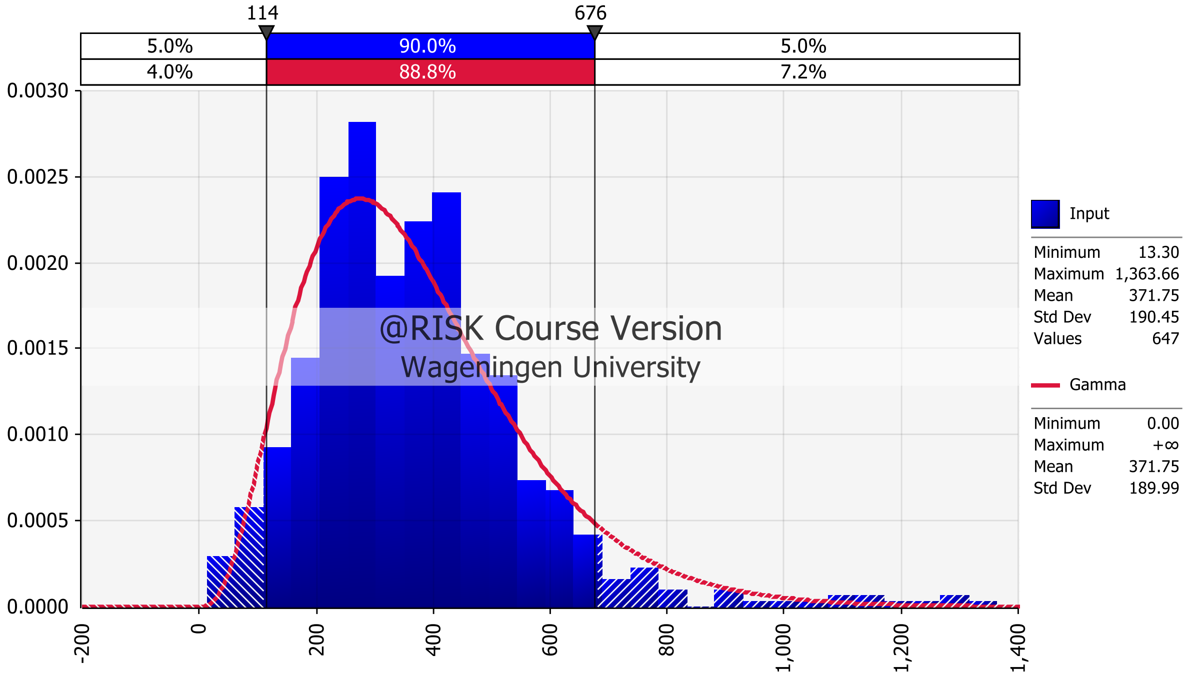

Figure A5. Distribution fitting for the variable costs of durum wheat. Source: own elaboration based on FADN data.