Bio-based and Applied Economics 9(1): 53-83, 2020
DOI: 10.13128/bae-7961

Full Research Article

Step-by-step development of a model simulating returns on farm from investments: the example of hazelnut plantation in Italy

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

Keywords. Perennial crop; real options; stochastic dynamic modelling; stochastic optimization.

JEL codes. C61, Q12.

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

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Editor: Fabio Gaetano Santeramo.

ISSN 2280-6180 (print)
ISSN 2280-6172 (online)

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.

The vast majority of research modelling farm-level investment behaviour opts for the classical investment theory, which maximizes the net present value (NPV) or alternatively the internal rate of return (IRR), or minimizes the pay-off period, subject to technological and resource constraints (e.g., Schweier and Becker, 2013; Shresta *et al.*, 2016; Bett and Ayieko, 2017). Two major limitations of this approach 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 risk underlying the investment project is not explicitly represented and can be reflected only by increasing the discount rate above market levels. Other data determining cash-flow changes of the operation related to the investment enter with their expected values, only, neglecting their riskiness including potential correlations. Second, the classical investment theory depicts a "now exactly as defined or never" decision problem where neither future adjustments to the investment project under, for instance, changing market, policy or technological environments, nor its postponement are considered. This easily overestimates necessary investment triggers and thus suggests a lower investment scale (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). But its empirical application is still limited, for instance, 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 recent studies, such as Sojkova and Adamickova (2011), consider risk. Not astonishingly, they find substantial differences in optimal investment levels compared to the classical NPV approach and suggest that deterministic models may provide flawed estimation of investment dynamics and scale.

Consideration of risks in investments is also beneficial for their social and behavioural analysis. Social analysis mainly focuses on social networks and their effects on investment decision, for instance, via learning experience (Marra *et al.*, 2003; Ghadim *et al.*, 2005). Dynamic social analysis is more promising and benefits from explicit consideration of risks, as learning and social interactions usually affect not only expectations, but also associated subjective risk; and optimal behaviour was found to be sensitive to strategic uncertainty (Morreale *et al.*, 2019). Behavioural investment analysis studies subjective factors, including irrationality, subjective beliefs, and risk attitude (see e.g., Chavas and Nauges, 2020; Weersink and Fulton, 2020). Also here, explicit consideration of risks in dynamics is beneficial as it allows adjusting risk perception and risk preferences (Coelho *et al.*, 2012). As for optimal financing behaviour, 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 *et al.*, 2012; Fecke *et al.*, 2016), farmer's personal characteristics and farm structural variables (Howley and Dillon, 2012). While financing behaviour is found to affect farm performance, financial risk, resilience, and their links to investment behaviour is still understudied.

Building on this literature, we develop models for valuing and analysing long-term investment decision on farm, starting with a simple net present value calculation. We stepwise expand this model to a final dynamic stochastic farm-scale simulation model inspired by real options approaches, which considers different financing options and downside risk aversion in the form of minimum household withdrawals. To this end, the paper focuses on economic analysis of farm-level investment and financing options, while some social and behavioural aspects might be incorporated in follow-up research as discussed in the concluding chapter. Accordingly, the objectives of the paper are twofold. First, we aim to illustrate how additional investment drivers can be stepwise incorporated into models of increasing complexity, and second, we aim to demonstrate sensitivity of results across the model variants to underline their relevance. The novelty of the paper 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 downside risk aversion of the farm household. Second, we stepwise introduce these factors to quantify their impact on optimal scale and timing of investments in a case study. Third, the case study refers to perennial crops, a domain where advanced quantitative assessments are lacking.

Hazelnut production was chosen for the empirical application. It presents an interesting case study 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 is not traditional, but becomes an increasingly important agricultural activity. The farm is assumed to currently manage rainfed annual crops. It is representative by its size and farm program for farms that are investing into new hazelnut plantations in the region. Since hazelnut production was found to be characterized by a relatively high level of risks (Zinnanti *et al.*, 2019), we explicitly quantify considerable market (Pelagalli, 2018), weather, and other production risks affecting product quality and quantity.

Taking hazelnut production in the Viterbo region as an example is motivated by further facts. Firstly, with 13% of global hazelnut production, Italy is the second largest producer worldwide after Turkey with ca. 65% (FAO, 2019). Global 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 a major one is located nearby our case study region. In Italy, further expansion of hazelnut orchards in the traditional hilly 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. Over the years 2016-2019, the Italian National Institute for Statistics (ISTAT) recorded a 15% increase in the total area devoted to hazelnut cultivations. Further investments are likely in coming years, according to major companies involved in hazelnut-based food production which foresee and foster the cultivation of 90.000 hectares in Italy alone. 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 ongoing 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 empirical analysis conducted in this paper closes the gap.

The paper is organized as follows. Section 2 step-by-step develops four models 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 shows the additional data required for the model expansions. Section 4 presents main empirical results to highlight differences across the model variants. Section 5 concludes with a discussion of pros and cons of the different model variants and provides suggestions for further research on farm investments.

2. Building-up a stochastic dynamic farm-level model

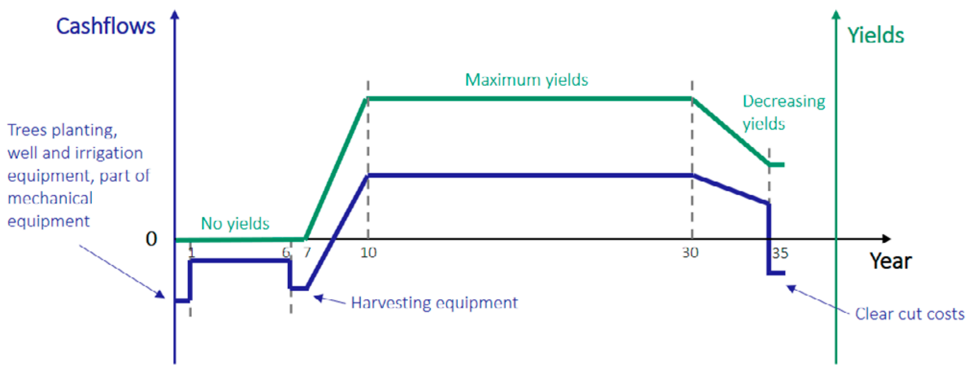
2.1 Farm-level endowments, economy-of-scale and alternative crop (ClassNPV)

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).

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 yields in year y is:

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

Figure 1. Evolution of a new hazelnut orchard, with related investments points. Source: Own elaboration based on Liso *et al*. (2017) and Frascarelli (2017).



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 tonnes per hectare [t ha^{-1}]; *maxYields* refers to 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 represented in the NPV calculation by their expectations. We also distinguish between harvesting costs per tonne harvested, and other costs 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:

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

where $E[\cdot]$ is the expectation operator; $gm_{hazel,y}$ stays for the gross margin of hazelnuts [€ ha^{-1}]; $qi_{hazel,y}$ for the hazelnuts quality index; $marketPrice_{hazel,y}$ for the average market price of hazelnuts [€ t^{-1}]; *harvCost* for the variable harvesting costs [€ t^{-1}]; *otherCost* 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 labour. Additional demand for labour can be satisfied via hired labour. 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 land endowment:

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

where $area_{hazel}$ depicts land under hazelnuts [ha] and $area_{wheat}$ land devoted to durum wheat [ha]; $\overline{end_{land}}$ stays for the total fixed and given land endowment [ha].

Labour requirement for the crops are expressed per hectare; for hazelnuts, additional labour hours per harvested tonne are considered. Total labour requirement can be covered by on-farm or hired labour:

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

where $\overline{lab_{wheat}}$ stays for labour requirements for durum wheat [hours per hectare, h ha^{-1}]; $\overline{lab_{hazel}}$ for quasi-fixed (i.e., independent of yields) labour requirements for hazelnuts [h ha^{-1}]; $\overline{lab_{hm}}$ for variable labour requirements for hazelnuts [hours per tonne, h t^{-1}]; end_{lab} for on-farm labour use [hours, h]; $hiredLab_{y}$ 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, namely, based on expected yield, quality index, market price and variable costs:

$$E[gm_{wheat}] = E[yield_{wheat}] * E[qi_{wheat}] * E[marketPrice_{wheat}] - E[cost_{wheat}] \tag{5}$$

where gm_{wheat} stays for gross margin of durum wheat [€ ha^{-1}]; $yield_{wheat}$ for its yields [t ha^{-1}]; qi_{wheat} for its quality index; $marketPrice_{wheat}$ for its average market price wheat [€ t^{-1}]; and $cost_{wheat}$ for its quasi-fixed costs [€ 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:

$$E[NPV] = \left(-iniCost + \sum_y \frac{E[gm_{hazel,y}]}{(1+dr)^y} - \frac{reconvCost}{(1+dr)^{35}} \right) * area_{hazel} + \sum_y area_{wheat} * \\ * E[gm_{wheat}] - invCostWell - \sum_y \frac{\sum_m invCostMach_{m,y} + hiredLab_y * E[wage]}{(1+dr)^y} \tag{6}$$

where NPV stays for the net present value over the overall planning horizon $\sum_y$ [€]; $iniCost$ for the costs associated with initial establishment of hazelnut plantation [€ ha^{-1}]; dr for the discount rate [%]; $reconvCost$ for the costs associated with final clear-cut of hazelnut plantation [€ ha^{-1}]; $invCostWell$ for costs of well and irrigation equipment for hazelnut [€]; $invCostMach_{m,y}$ for investment costs of machinery m{*smaller;standalone;irrigation;tractor; operating*} [€]; $E[wage]$ for expected costs of hired labour [€ h^{-1}]. We optimize the farm-level NPV under endowment constraints (Eq. 3 and 4) 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 by accounting for all 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.

This model still suffers from limitations as seen in literature. First, it operates with expected 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 of hazelnut, and motivate 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 also considers risks besides (quasi-fixed) assets, such as land and on-farm labour already found in the model *ClassNPV* above, and addresses both time and scale flexibility as elements of a real-options approach. Spiegel *et al.* (2018; 2020) overcome the curse of dimensionality found in binary lattices or similar scenario tree approaches by employing a scenario tree reduction technique. 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 an infinite one become marginal from a numerical perspective.

We assume the following aspects of management flexibility. The farmer can decide during the first five years 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 land endowment (*scale flexibility*). Using fixed plot sizes instead of a continuous fractional plantation size allows for a mixed integer program instead of a mixed non-linear integer one. Integers are needed anyhow to capture indivisibilities in investment (well, machinery). Time flexibility is considered separately for each plot.

Differences compared to the previous model *ClassNPV* are threefold. First, we consider now not only the expected values of stochastic variables, but also the associated riskiness. More specifically, all expected values 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. Second, we now distinguish between the time period and the 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 to introduce hazelnuts or not. Accordingly, a plantation now can consist of plots of different age. As a consequence, in the expanded model, decision variables and risky parameters carry now both a time and node indices, such that the gross margins of both crops are defined as follows:

$$gm_{hazel,p,t,n} = ha_{hazel,p,t,n} * [\, yield_{hazel,p,t,n} * qi_{hazel,t,n} * marketPrice_{hazel,t,n} - yield_{hazel,p,t,n} * harvCost - otherCost] \tag{7}$$

$$gm_{wheat,t,n} = yield_{wheat,t,n} * qi_{wheat,t,n} * MarketPrice_{wheat,t,n} - cost_{wheat,t,n} \tag{8}$$

where $gm_{hazel,p,t,n}$ stays for the gross margin of hazelnuts [€ ha^{-1}] on plot p in time period $t\{t_1,t_2,\ldots,T\}$ and node of the scenario tree n; $yield_{hazel,p,t,n}$ for hazelnut yields [t ha^{-1}] on plot p in time period t and node of the scenario tree n. The hazelnut yield depends on the difference between current year t and the year $\tilde{t}$ when they were planted on this plot on the same path from the root to the current node n according to Eq.(1). $ha_{hazel,p,t,n}$ 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); $qi_{hazel,t,n}$ for the hazelnuts quality index in time period t and node of the scenario tree n; $marketPrice_{hazel,t,n}$ for the market price of hazelnuts in time period t and node of the scenario tree n [€ t^{-1}]; $gm_{wheat,t,n}$ for gross margin of durum wheat [€ ha^{-1}] in time period t and node of the scenario tree n; $yield_{wheat,t,n}$ for yields of durum wheat [t ha^{-1}] in time period t and node of the scenario tree n; $qi_{wheat,t,n}$ for quality index of durum wheat in time period t and node of the scenario tree n; $MarketPrice_{wheat,t,n}$ for the market price of durum wheat [€ t^{-1}] in time period t and node of the scenario tree n; $cost_{wheat,t,n}$ for quasi-fixed costs for durum wheat [€ ha^{-1}] in time period t and node of the scenario tree n.

The farm's operating income is thus defined as follows:

$$operInc_{farm,t,n} = area_{wheat,t,n} * gm_{wheat,t,n} + \sum_p size_p * gm_{hazel,p,t,n} - \sum_p ini_{p,t,n} * iniCost * size_p - \sum_p reconv_{p,t,n} * reconvCost * size_p - invWell_{t,n} * invCostWell - \sum_m invMach_{m,t,n} * invCostMach_m - hiredLab_{t,n} * wage_{t,n} \qquad \forall t,n \tag{9}$$

where $operInc_{farm,t,n}$ stays for farm's operating income in time period t and node of the scenario tree n [€]; $area_{wheat,t,n}$ for land area under durum wheat in time period t and node of the scenario tree n [ha]; $size_p$ for the size of the plot p [ha]; $ini_{p,t,n}$ for a binary variable of exercising the initial establishment of a hazelnut plantation on plot p in time period t and node of the scenario tree n (1 = hazelnuts are introduced; 0 = otherwise); $reconv_{p,t,n}$ 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); $invWell_{t,n}$ 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); $invMach_{m,t,n}$ 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 the objective variable to be maximized, defined as follows:

$$NPV = \sum_{t,n} prob_n * \frac{operInc_{farm,t,n}}{(1+dr)^t} \tag{10}$$

where $prob_n$ stays for the probability of the node 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 allows to observe (re)planting decisions, as well as decisions to expand or clear-cut hazelnut plantations;
- 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 presumably closer to real world decisions on investments, it has still two major drawbacks considering gaps found in literature. First, 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. Related costs for financing are most probably underestimated by the average discount rate in the model. Second, the model neglects downside risk aversion, while the production cycle of hazelnuts implies significant negative cash flows in several time periods and related financing costs. We address these 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 annual profit withdrawals from the current account of the farm, discounted by his private discount rate. Accordingly, the private 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:

$$curAcc_{t,n} = \sum_{n1-n=1} curAcc_{t-1,n1} + operInc_{farm,t,n} - withdraw_{t,n} + \sum_{loans} newLoans_{loans,t,n} - \sum_{loans} repaym_{loans,t,n} - \sum_{loans} intpaym_{loans,t,n} \qquad \forall t, \tag{11}$$

where $curAcc_{t,n}$ stays for the current account in the year t and node n [€]; $withdraw_{t,n}$ for annual farm household withdrawals [€]; $newLoans_{loans,t,n}$ for the loans acquired in the year t and node n [€]; $repaym_{loans,t,n}$ for the debt to-be-paid in the year t and node n [€]; and $intpaym_{loans,t,n}$ 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 that introducing endogenous financing decisions implies and requires a more accurate simulation of cash flows. In particular, if the previous two models could omit cash flows independent of investment decisions, such as decoupled subsidies under the Common Agricultural Policy's (CAP) first pillar, all cash flows related to the farm operation have to be included now, since they affect the required financing. The operating income is hence defined as:

$$operInc_{farm,t,n} = area_{wheat,t,n} * gm_{wheat,t,n} + \sum_{p} size_p * gm_{hazel,p,t,n} - \sum_{p} ini_{p,t,n} * iniCost * size_p - \sum_{p} reconv_{p,t,n} * reconvCost * size_p - invWell_{t,n} * invCostWell - \sum_{m} invMach_{m,t,n} * invCostMach_m - hiredLab_{t,n} * waget,n + end_{land} * prem \quad \forall t,n \quad (12)$$

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:

$$NPV = \sum_{t,n} prob_n * \frac{withdraw_{t,n}}{(1+dr)^t} \quad (13)$$

2.4 Downside risk aversion (RealOptFinRisk)

Explicitly considering profit withdrawals allows introducing a lower limit of income from the farm operation such as to ensure household survival. This 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 nodes 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 and each node of the scenario tree. It is calculated by multiplying the level of the farm resource endowments with assumed minimum risk-free returns:

$$withdraw_{t,n} \geq end_{lab} * minWage + end_{land} * prem \quad (14)$$

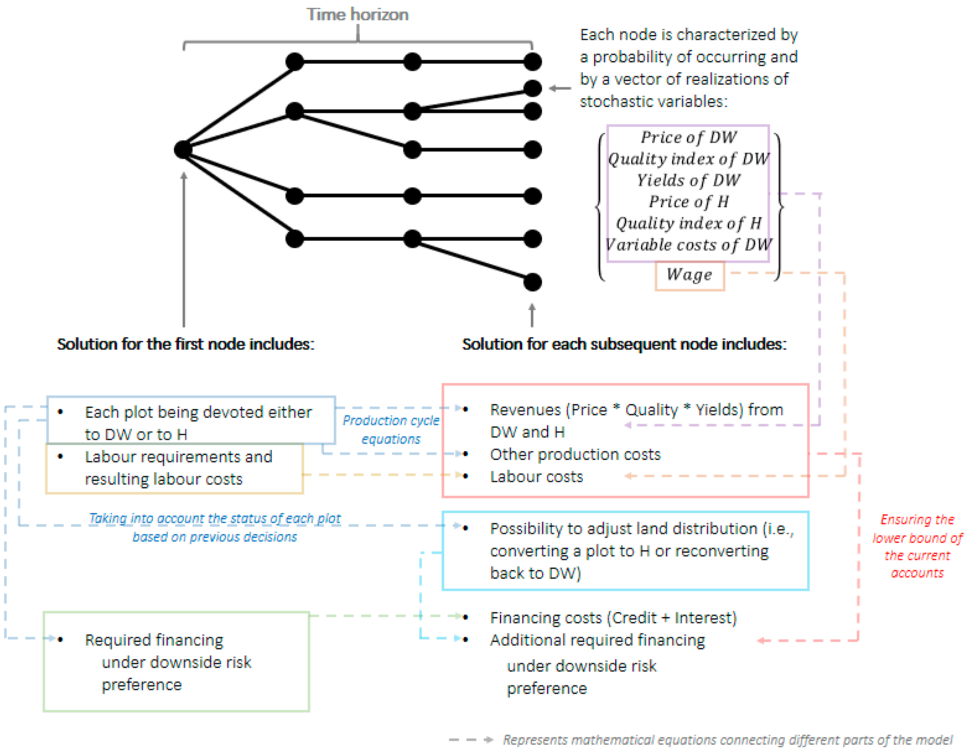
where *minWage* is a minimum risk-free off-farm wage [€ h^{-1}]. Similar, the minimum withdrawal limits above assumes that the farmer would be able to receive at least the premium of the first pillar of CAP as returns to its land, for instance, by renting it out. Different assumptions to define minimum withdrawals could clearly be chosen.

Financing and deciding on the annual 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 annual 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 his expected discounted income level. It does not require to introduce explicitly a risk-utility function in the framework above which is another avenue to develop the model further, for instance, to introduce behavioural aspects.

Figure 2 graphically represents the model variant 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 reflect set-up and removal decisions with respect to hazelnuts made in this one and its ancestor nodes. These decisions translate into the future according to the production cycle and determine required future financing, as well as future costs of adjusting these production decisions. Financing decisions need to ensure minimum household withdrawals and a non-negative current account. The model simultaneously solves for optimal behaviour in all its nodes, maximizing the net present value (Eq. 13) under endowment and other constraints.

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.

2.5 Comparison of the models

Fig. 3 and Table 1 below give an overview on the four model variants. *ClassNPV* calculates discounted annual 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 labour might be needed depending on available farm family labour and the chosen investment program. *RealOpt* adds time flexibility, i.e., it captures and optimizes returns from investments 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 financing decisions. *RealOptFinRisk* finally ensures that the farm household 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 model variants.

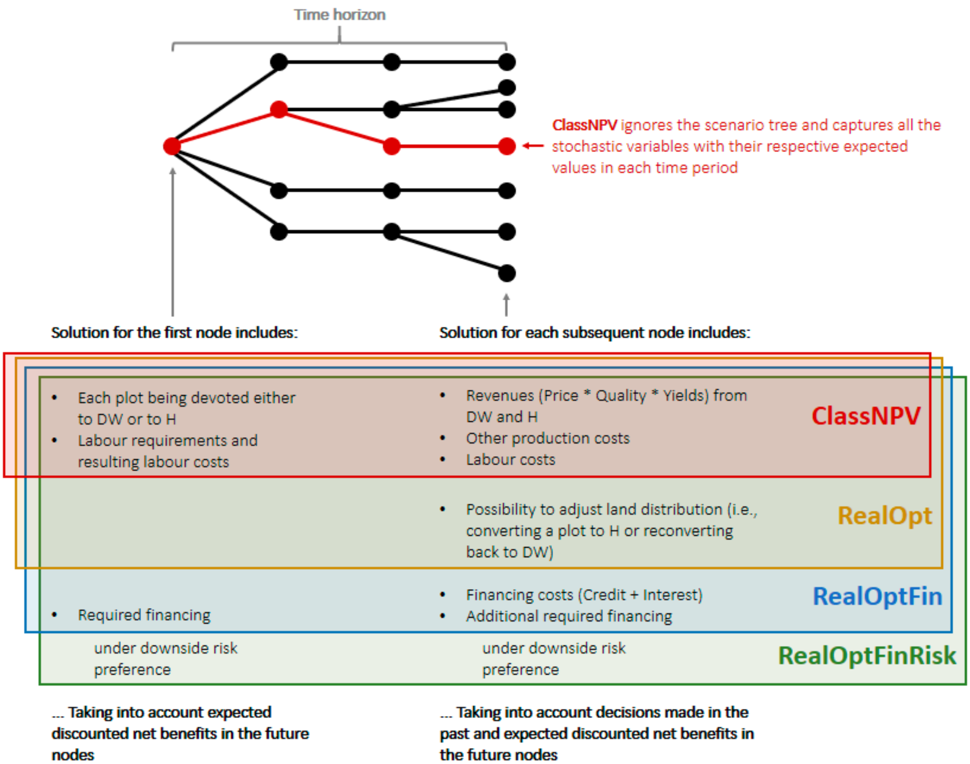


Table 1. Comparison of the four model variants.

		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

2.6 Solution approach

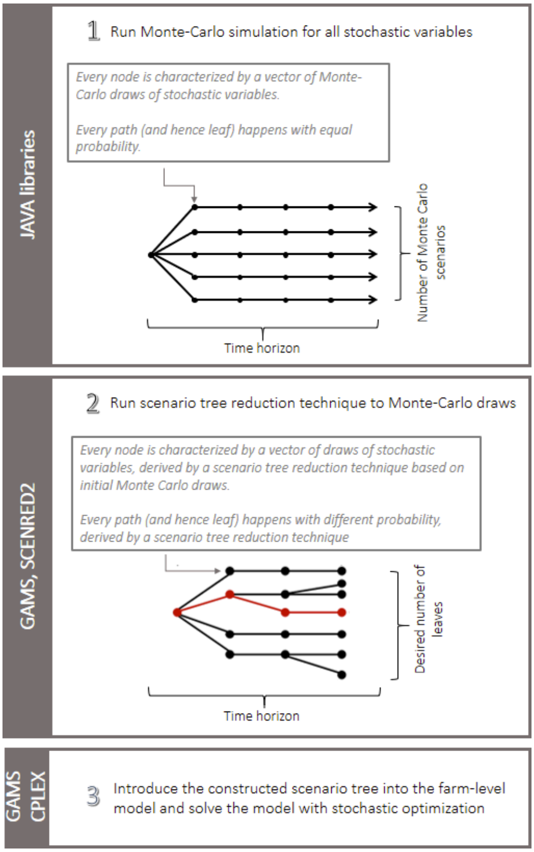
We use the solution approach suggested by Spiegel *et al.* (2018; 2020), which combines Monte-Carlo simulation, a scenario tree reduction technique, and stochastic-dynamic programming (Fig. 4). First, 5’000 Monte-Carlo draws are obtained for all the stochastic variables, using empirically predefined 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 this 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 behaviour 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.

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

Figure 4. Graphical representation of the solution process. (Source: based on Spiegel *et al.*, 2018; 2020).



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. Data have been retrieved from the individual farm FADN database (2008-2016) considering only 21 municipalities of the province of Viterbo[1] (Lazio region) where hazelnut represents a limited share of the Utilized Agricultural Area according to 2010 Census data (less than 5%), but which have recently experienced relevant relative increases due to new plantations. We furthermore filter FADN data 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

[1] Arlena di Castro, Bassano in Teverina, Blera, Castel Sant'Elia, Celleno, Civita Castellana, Gradoli, Graffignano, Marta, Monte Romano, Montefiascone, Monterosi, Oriolo Romano, Orte, Piansano, Tuscania, Vejano, Vetralla, Villa San Giovanni, Vitorchiano in Tuscia, Viterbo.

after planting (Frascarelli, 2017). Second, only observations above 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 2 provides an overview of the parameter values and underlying 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). Also, due to limited data on hazelnut yields, we assume no riskiness in maximum hazelnut yields *maxYields* and the yields derived thereof $yield_{hazel,p,t,n}$. Instead, stochasticity in hazelnut production is captured by a stochastic quality index and market price. 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, we correct the expected hazelnut price derived from historical observations by a multiplicative coefficient of 1.18. Assuming higher future prices seems appropriate due to increasing global demand of hazelnut, while production is expanding into less suitable production areas with a lower yield potential and higher costs, such caused by the required irrigation. Furthermore, all four models suggest no investments at all into hazelnuts under the expected historical price level. This contradicts observed farmers’ behavior, and suggests that farmer expect higher future prices. We used sensitivity analysis to find a suitable future expected mean price level where some but not all land was devoted to hazelnut in at least one of the models, reflected by the factor of 1.18.

For quality indices, the FADN data were used to derive annual 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 labour needs and has a longer lifetime measured in harvested area.

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

$$dprH_t = \mu_{hazel}\,(\theta_{hazel} - prH_t)dt + \sigma_{hazel}\,dW_t^{hazel} \tag{15}$$

$$dprDW_t = \mu_{wheat}\,(\theta_{wheat} - prDW_t)dt + \sigma_{wheat}\,dW_t^{wheat} \tag{16}$$

where t is the time period; *hazel* indicates hazelnuts and *wheat* durum wheat; prH_t is the natural logarithm of hazelnuts price; $prDW_t$ the natural logarithm of durum wheat price;

Table 2. Overview of parameters of the four models, their assumed values, and respective references.

Model	Parameter	Notation used in equations above[1]	Value	References
ClassNPV	Expected yields of durum wheat	$E[yield_{wheat}]$	3.9 t ha^{-1}	FADN
	Expected variable costs of durum wheat	$E[cost_{wheat}]$	371.75 € ha^{-1}	FADN
	Expected market price of durum wheat	$E[marketPrice_{wheat}]$	237.22 € t^{-1}	Eurostat, Word Bank
	Expected market price of hazelnuts	$E[marketPrice_{hazel}]$	2,549.66 € t^{-1}	ISTAT, Word Bank
	Expected quality index of durum wheat	$E[qi_{wheat}]$	0.9247	FADN, ISTAT
	Expected quality index of hazelnuts	$E[qi_{hazel}]$	0.9817	FADN, ISTAT
	Expected wage of hired labour	$E[wage]$	10 € h^{-1}	Local collective contracts for hired labour
RealOprFinRisk RealOptFin RealOpt	Available annual labour endowment	end_{lab}	350 h	Own elaborations
	Available land endowment	end_{land}	30 ha	FADN
	Hazelnut establishment costs	$iniCost$	8,000 € ha^{-1}	Liso *et al.*, 2017; Ribaudo, 2011; Frascarelli, 2017
	Investments for a smaller harvesting machinery	$invCostMach_{smaller}$	8,000 €	Liso *et al.*, 2017; Ribaudo, 2011; Frascarelli, 2017
	Labour requirements for a smaller harvesting machinery		32 h ha^{-1}	Liso *et al.*, 2017; Ribaudo, 2011; Frascarelli, 2017
	Maximum land area that can be harvested per year with a smaller harvesting machinery		5 ha	Liso *et al.*, 2017; Ribaudo, 2011; Frascarelli, 2017
	Total endowment for a smaller harvesting machinery			
	In terms of lifetime		12 years	Liso *et al.*, 2017; Ribaudo, 2011; Frascarelli, 2017
	In physical terms		2,000 h	Liso *et al.*, 2017; Ribaudo, 2011; Frascarelli, 2017
	Investments for a stand-alone harvesting machinery	$invCostMach_{standalone}$	40,000 €	Liso *et al.*, 2017; Ribaudo, 2011; Frascarelli, 2017
	Labour requirements for a stand-alone harvesting machinery		15 h ha^{-1}	Liso *et al.*, 2017; Ribaudo, 2011; Frascarelli, 2017
	Maximum land area that can be harvested per year with a smaller harvesting machinery		15 ha	Liso *et al.*, 2017; Ribaudo, 2011; Frascarelli, 2017
	Total endowment for a smaller harvesting machinery			
	In terms of lifetime		12 years	Liso *et al.*, 2017; Ribaudo, 2011; Frascarelli, 2017
	In physical terms		3,000 h	Liso *et al.*, 2017; Ribaudo, 2011; Frascarelli, 2017
	Other labour requirements for hazelnut (excl. labour required for harvesting machines)			

Model	Parameter	Notation used in equations above[1]	Value	References
	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	*harvCost*	50 € t^{-1}	Ribaudo, 2011
	Other production costs of hazelnuts, incl.	*otherCost*	1,700 € ha^{-1}	Expert based information
	Costs of fertilization 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	*invCostWell*	12,000 €	Liso *et al.*, 2017; Ribaudo, 2011; Frascarelli, 2017
	Investments into irrigation equipment for hazelnuts	$invCostMach_{irrigation}$	2,000 € ha^{-1}	Liso *et al.*, 2017; Ribaudo, 2011; Frascarelli, 2017
	Investments into tractor	$invCostMach_{tractor}$	20,000 €	Expert based information
	Lifetime of tractor		20 years	Ribaudo, 2011
	Investments into operating machinery for hazelnuts	$invCostMach_{operating}$	10,000 €	Expert based information
	Lifetime of operating machinery		10 years	Ribaudo, 2011
	CAP direct payment	*prem*	300 € ha^{-1}	Own elaboration
	Annual discount rate	*dr*	2%	Own elaboration
	Laplace distribution for yields of durum wheat (see Appendix for further details)			
	Mean		3.9120	FADN
	Standard deviation		1.1984	FADN
	Expected maximum yields of hazelnuts	*maxYields*	2.9 t ha^{-1}	FADN
	Mean-reverting stochastic process for natural logarithm of market price of durum wheat (see Appendix for further details)	$marketPrice_{wheat}$		
	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

Model	Parameter	Notation used in equations above[1]	Value	References
	Mean-reverting stochastic process for natural logarithm of market price of hazelnuts (see Appendix for further details)	$marketPrice_{hazel}$		
	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 (see Appendix for further details)	qi_{wheat}		
	Mean		0.9817	ISTAT
	Standard deviation		0.2580	ISTAT
	Laplace distribution for quality index of hazelnuts (see Appendix for further details)	qi_{hazel}		
	Mean		0.9247	ISTAT
	Standard deviation		0.2398	ISTAT
	Gamma distribution for variable costs of durum wheat (see Appendix for further details)	$cost_{wheat}$		
	Shape		3.8286	FADN
	Scale		97.098	FADN
	Uniform distribution for costs of hired labour	$wage$		
	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	$minWage$	6 € h^{-1}	Expert based information

[1] Indices *y*, {*t*,*n*} and {*p*,*t*,*n*} are omitted for simplicity.

μ the speed of reversion; θ the long-term logarithmic average level of price; σ the standard deviation; and dW_t^{hazel} the standard Brownian motion independent from dW_t^{wheat}. Other stochastic variables, namely a quality index of hazelnuts and a quality index, yield and variable costs of durum wheat are captured by distributions that were selected based on Akaike Information Criteria (AIC) (Akaike 1998) using @RISK software. More details on deriving the stochastic processes and distributions based on historical data are presented in the Appendix.

4. Results and discussion

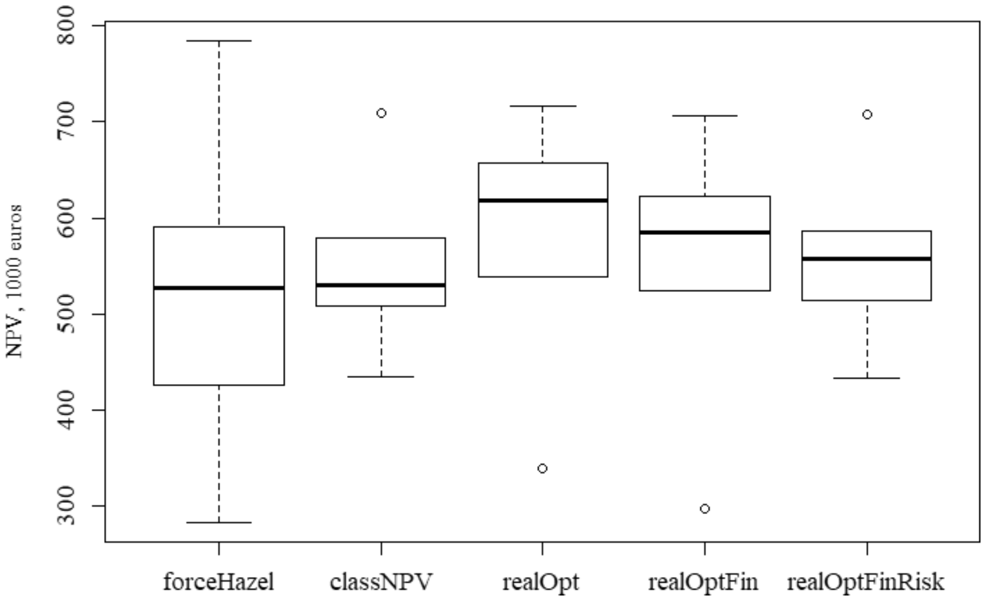
We focus in this section on differences between the models with respect to key results: scale and timing of optimal hazelnuts introduction, expected NPV, as well as financing decision (Table 3). In particular, according to the *ClassNPV* model, hazelnuts cannot compete with the representative alternative arable crop durum wheat. Accordingly, the expected NPV of *ClassNPV* (rows 4-5 in Table 3) 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% is hence an expected share. Row 2 in Table 3 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 *RealOptFin* to opportunity costs reflecting off-farm wages and renting out land. Durum wheat exceeds these opportunity costs in any year and node, but hazelnuts do not. Accordingly, the *RealOptFinRisk* model has to postpone investments until hazelnuts are only introduced on such nodes where the minimal income of farming exceeds opportunity costs. For the remainder of the stochastic tree, only durum wheat is cropped. Compared to *RealOpt* or *RealOptFin*, this implies a lower average discounted household income at however reduced downside risk.

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 under assumed loan conditions. 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 exceeds the one of the *ClassNPV* model by 0.6%. Fig. 5 compares the riskiness of the resulting NPV in the four models described above, plus the *forceHazel* variant which forces immediate conversion of the whole farm

Table 3. Comparison of empirical results of different models.

	ClassNPV	RealOpt	RealOptFin	RealOptFinRisk
(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	-	(in 2 years)	(in 2 years)	(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

Figure 5. Distributions of maximized net present values in the five model variants, incl. *forceHazel* – an additional model variant 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.



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 devoting all resources to hazelnuts, the latter to the alternative crop. Both deterministic models *forceHazel* and *classNPV* ignore any risk by using expected values, only, for any stochastic variable related to both hazelnuts and the alternative crop durum wheat. We however recovered the associated riskiness in resulting NPVs post-model 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 annual household withdrawals, however as noted already above, at the costs of a lower expected NPV (Fig. 5). The *realOpt* and *realOptFin* show some outliers (indicated as dots in the box-and-whisker charts) with quite low NPVs that are removed at the *RealOptFinRisk* model, which however also considerably reduces upside risk.

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.

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 3, row (7)) to finance the initial investment costs of plantation set-up and the well, as well as in some later years investment in a harvester. The costs relate to an expected 41% land share under hazelnuts (Table 3, 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 3, 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

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

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.

The empirical results are in line with the available literature. Comparison of the results of *ClassNPV* and *RealOpt* models indicate that uncertainty and time flexibility leads to later investments at a higher expected scale. Trigeorgis and Reuer (2017) and Musshoff (2012) confirm that managerial flexibility usually increases the value of waiting, hence leading to postponement of investments; the reader should note here that relatively small uncertainty might lead to no value of waiting and hence immediate investments. As for investment scale, Hassett and Metcalf (1993) confirm that if immediate investment is worthless, uncertainty could create its value in the future. However, the effect of uncertainty might be the opposite if immediate exercising of investment is profitable in a risk-free environment. In this case, considering temporal flexibility might lead to lower expected investment scale depending on how the stochastic environment evolves. The resulting effect would depend on the underlying uncertainty, as well as on relationship between stochastic variables and the optimal investment scale. In this regard, our empirical results stating that uncertainty leads to larger expected area under hazelnuts shall be treated as a special case. Trigeorgis and Reuer (2017) also report that managerial flexibility reduces downside riskiness of investment, which is confirmed by our results, in particular the upper part of Fig. 6. Comparison of the results of *RealOpt* and *RealOptFin* models suggest that explicit consideration of financing behaviour reduces investment scales, yet does not affect the earliest time of investments. The results can indirectly be confirmed by Chen (2003) and Lin (2009), both claiming that a higher debt ratio leads to a higher investment threshold. However, we explicitly highlight here that the literature focusing on financing of investment under uncertainty is extremely limited. Finally, comparing the results of *RealOptFin* and *RealOptFinRisk*, one can conclude that consideration of downside risk aversion leads to later investment at a lower scale, as well as lower resulting riskiness. Previous studies confirm that risk aversion, and downside risk aversion in particular, reduces incentives to invest (e.g., Chronopoulos *et al.*, 2011).

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 and can provide more detailed advice to decision takers, 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 elements 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 downside risk, but also shows the resulting consequences on the scale and timing of investments, as well as on financing behaviour.

Clearly, there is a trade-off between additional insights and potentially more realistic results on the one hand, and increased data demands (Table 2) and model complexity on the other one. 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 to sensitivity analysis to inform on their importance individually. Furthermore, such sensitivity analysis could also help to find a set of parameters which best fits the observed behaviour (e.g. Troost and Berger, 2014). In our case, expected hazelnuts yields and market prices as well as 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 complement the optimization model with other methodologies (Colen *et al.*, 2016), for instance, to expose farmers facing investment decisions to results of such models in order to learn more, e.g., on 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. Alternatively, results obtained with other methodologies, e.g., econometric or experimental techniques for objective or constraint functions, can serve as input for optimization model and allow introducing behavioural aspects, for instance in form of a risk utility function (Chronopoulos *et al.*, 2014). Finally, further research might put greater focus on how learning affects future expectations, for instance, how experiences of rare but catastrophic events shape expectations, and how this can be reflected, for instance, in a scenario tree.

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. We demonstrated the different models using the example of hazelnut production in an Italian region. An application to, for instance, other perennials can draw on the basic model structure and solution approach. But it will clearly require other data, and potentially also adjustments in some model detail, for instance introducing variables and equations to reflect additionally required investments such as relating to storage or post-harvest treatment.

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

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).

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

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.

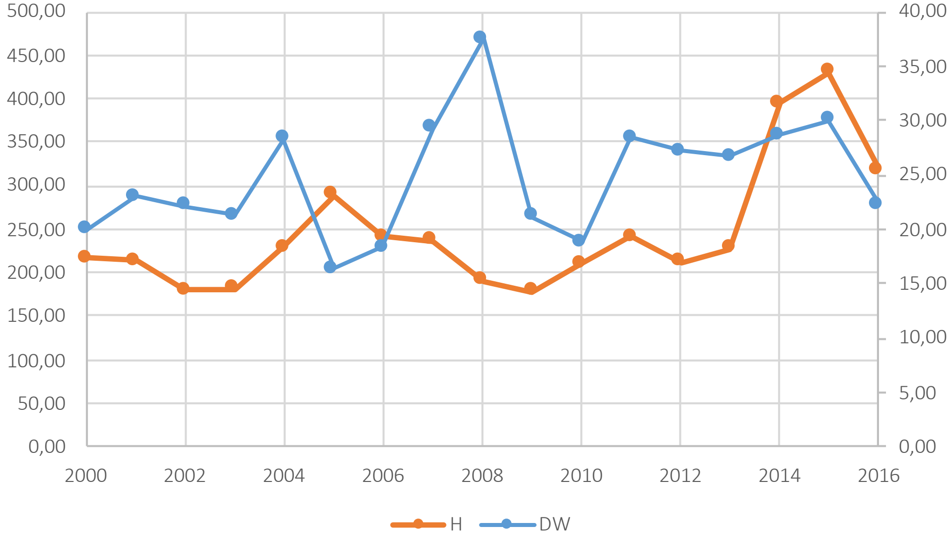


Table A1. Estimated parameters of mean-reverting processes for hazelnut and durum wheat prices. Source: own estimation based on the ISTAT (for hazelnuts, years 2000-2013) and Eurostat (for durum wheat, years 2000-2016, excl. 2008) data. The prices were deflated (2015=100) using the GDP deflator for Italy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

reflecting that the market price likely fluctuates around a constant long-term per unit production cost. The result of the MRP estimations are summarized in the Table A1.

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.

Quality index for hazelnut and durum wheat

The FADN data were used to derive annual per unit farm specific prices of hazelnuts and durum wheat by dividing crop revenues by sold quantities. These calculated farm-gate

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

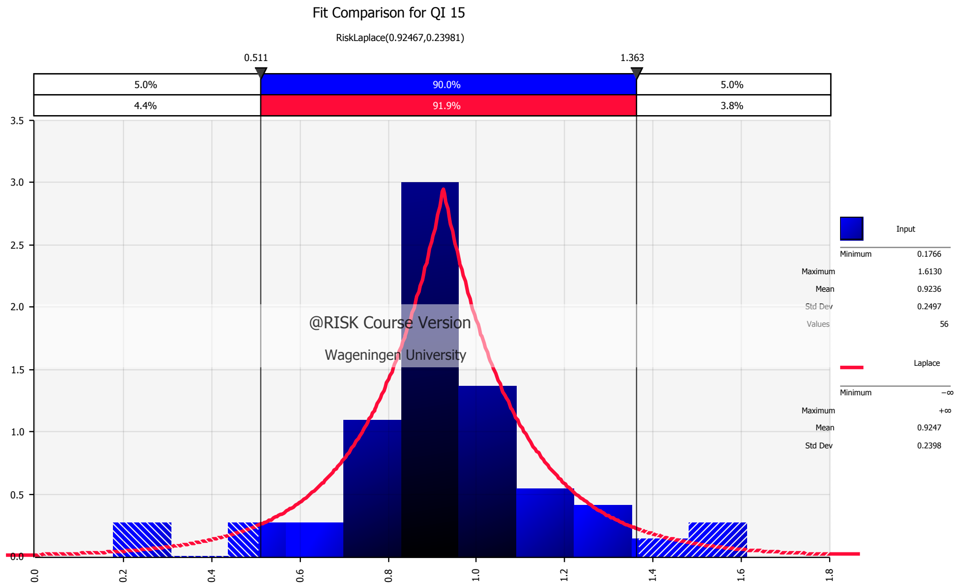
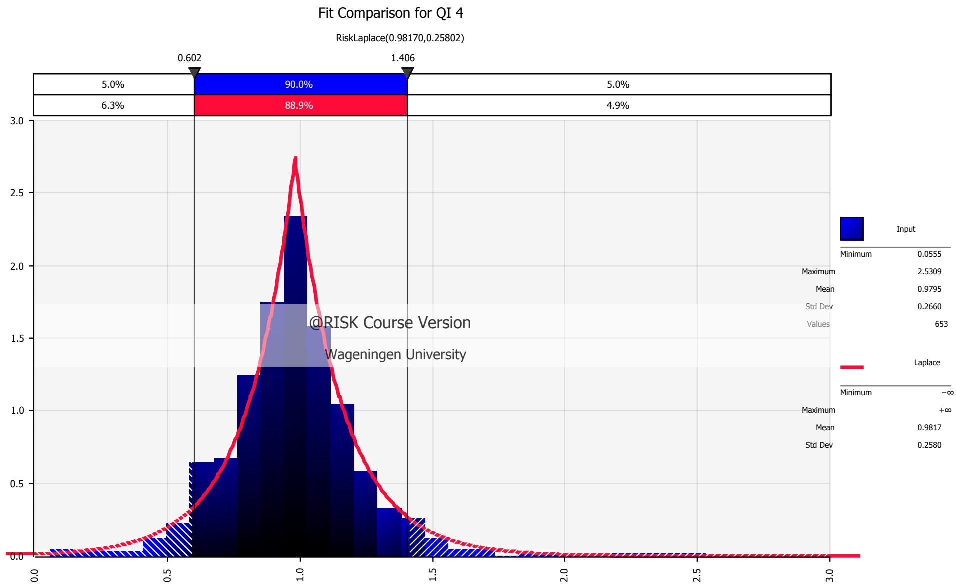


Figure A3. Distribution fitting for the quality index of durum wheat. Source: own elaboration based on FADN and Eurostat data.



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.

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.

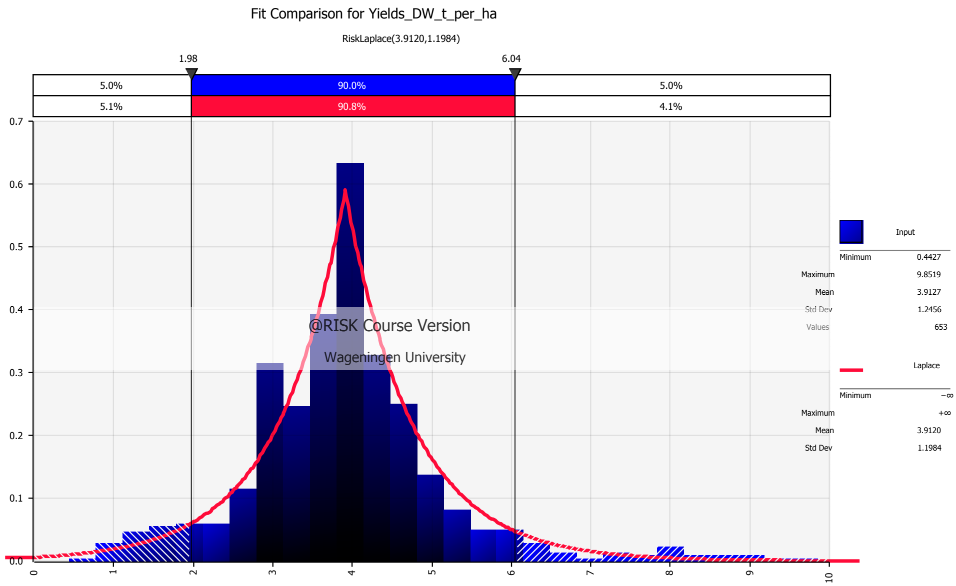


Figure A5. Distribution fitting for the variable costs of durum wheat. Source: own elaboration based on FADN data.