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Optimising adaptation decisions in macadamia production using contingent claim valuation

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Altering production systems and land management of tree crops is a costly, disruptive and ultimately irreversible decision. Using traditional valuation methods to appraise long-term land management outcomes ignores the full impact of irreversible or delayed decisions. We employ a variant of the real options decision process to examine uncertainties around climatic effects on macadamia growers and the explicit decision to adapt via cultivar replacement. We examine the trade-offs between the timing of the decision to replace macadamia cultivars by considering both the value of flexibility as well as the value of new information that can be used to resolve uncertainty. We compare the relative responses that generate the most value for growers across four geographical locations. We show that simple switching decisions using traditional valuation methods are found to be suboptimal and initiate poor decisions, potentially undermining adaptation efforts. As the rate of orchard degradation increases, the need to transition to higher-yielding cultivars becomes greater, especially for Hawaii, California and Australia where gross margins are leaner. Investment decisions are thus highly dependent on both local conditions and the economic structure of existing production systems.

Key words: binomial model, investment optimisation, macadamia, net present value, real options, sequential compound options.

1. Introduction

Decisions made by growers in response to shifting climatic conditions have long-lasting effects on agricultural productivity. In particular, decisions relating to the replacement of cultivars in orchards with higher-yielding heat/humidity-resistant breeds are irreversible and very costly if the decision to switch is mistimed. Choosing the optimal point at which to adapt is thus made difficult by the effect of climate uncertainty and variability on decision thresholds.

In practice, growers have the flexibility to respond to both shifting environmental conditions and farm produce prices in two important ways. First, they can choose to switch a proportion of their orchard at discrete points in time to more appropriate cultivars. Second, they can choose to delay the replacing of cultivars if economic conditions are unfavourable. A grower can then maintain a baseline level of income from the existing orchard coupled with the upside of investment returns from gradual cultivar

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replacement. The challenge is to evaluate the optimal rate of replacement given a range of economic conditions. We assume that growers embark on an adoption approach in response to climate change in contrast to the adaptation response defined in Zilberman *et al*. (2012).

Adapting production systems through land-use management to better cope with climate variability are irreversible decisions. Traditional valuation methods such as net present value (NPV) analysis to appraise investments of this type ignore the full value inherent in delayed decisions and the embedded costs of irreversible ones. Adopting a contingent-claims (or real options) valuation method, in contrast, fully accounts for both one-off and sequential adaptation decisions.

The decision to switch portions of an operation can be represented using a model that values sequential compound options for a multistage project with varying margins and switching times, while holding input costs constant. This approach allows a grower to determine the optimal balance between waiting for more information and the cost of waiting, which approximates the expected value of perfect information. The balance is optimised by creating strategic options to defer investment into discrete stages where the value of cultivar replacement is re-evaluated.

We construct real option values incurred by macadamia growers in four distinct locations to measure the optimal decision points for crop transfer in response to altered climatic conditions. We adopt an approach that is a theoretical extension to the study of land-use regime switching conducted by Sanderson *et al*. (2016) with the added ability to maximise enterprise value by *ex ante* estimating the full range of possible cultivar replacement periods available to a farmer. The Sanderson *et al*. (2016) approach assesses optimal land-use regime switching times for an entire enterprise while our approach identifies both the times and relative proportion of cultivars to switch that maximises enterprise value. Our approach uses a sequential compound option process for valuation which derives a solution that computes the sequential option prices as a single step. This ensures internal consistency of the solution at any time during the investment horizon considered by the farmer.

The subtleties within real options theory permits deeper understanding of how future risk and uncertainty play into the grower's decision today and at discrete points in the future. We show that the decision to switch cultivars along with the proportion that is switched is a strong function of expected price and a weak function of operating costs. The analysis shows that no more than one-fifth of an average orchard should be switched in any 5 to 7 year period. This indicates that the adaptation cycle of macadamia farmers may extend out as far as 35 years. This adaptation cycle may extend beyond the climatic cycle and cause distress on existing cultivars which may impact future production. While macadamias have been used in this analysis, the approach could be easily adapted to other horticultural crops including apples, citrus, bananas, mangoes, avocados, papaya and lychees.

2. Macadamia production

Macadamia nut is native to Australia but was only commercially developed after Hawaiian growers successfully developed a macadamia nut industry following the tree's introduction to the islands as a windbreak for sugarcane plantations. Ecological modelling suggests that climate change will reduce both the volume and quality of macadamia nut production in Hawaii, Southern California, Australia and South Africa, where the bulk of the global production of this nut variety is concentrated (Reid 2002). Mature macadamia production systems dependent on older cultivars are at the extreme of individual species' latitudinal range and are being affected by climate-induced variation in both temperature and rainfall. Climate cycles affect the timing of phenology, the initiation of flowering pollination vectors and the maturation of fruit (Hardner *et al.* 2009). The range overlap of various species, which are known to have considerable variation in timing of phenology, is expected to result in increased potential for hybridisation between the species. On the other hand, climate change may exacerbate other existing threats such as pests, fire and weeds, creating additional concerns for land managers seeking to develop new hybrids. Newer hybrids are showing initial signs of higher production volumes along with lower annual variability in both volume and quality (Wallace and Walton 2011).

Similar to other tree nut crops, macadamias experience production in the fourth or fifth year after planting and fully mature after about 12–16 years. Yields vary with location, season, variety and grower expertise but typical farms have around 300 trees per hectare with peak yields at maturity of 3.5–4 tonnes of nut in shell (NIS) per hectare. Prices are paid at a benchmark level of 33% sound kernel recovery, 3.5% maximum unsound kernel recovery and 10% moisture content. The price and production series for Australian macadamia NIS is provided in Figure 1 (prices are representative of world NIS prices, production data unavailable for other countries back to 1987).

Macadamia production practices and cost structures differ across geographical regions. Concentration levels among growers are high in Australia and Hawaii, but more dispersed in California and southern Africa. Production costs also vary across countries with labour-intensive methods in southern Africa compared with mechanical harvesting and farm management in California, Hawaii and Australia (Figure 2).

Approximately 4,000 growers operate across these four regions with an average orchard size of 20 hectares, although some operations are as large as 600 hectares. Most of the mature farms use varieties developed in Hawaii such as HAES 246 (Keauhou), HAES 344 (Kau), HAES 741 (Mauka) and HAES 660 (Keaau). But the incentives for newer varieties such as Hidden Valley A4 and Hidden Valley A16 are driven by the preference for higher-yielding and heat-tolerant produce. Annual operating costs vary across regions from $1,600 to $3,500 per hectare which includes fertilising, mulching, pest, disease and weed control, tree training, machinery operating

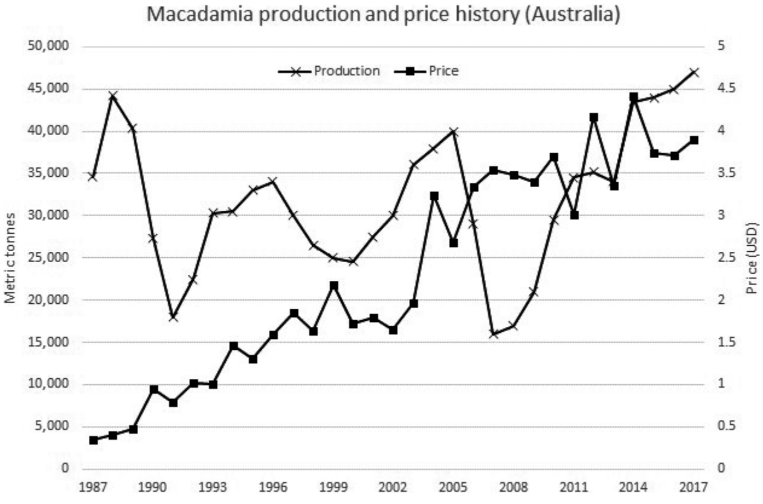

Figure 1 Macadamia nut in shell (NIS) price and volume history for Australia, 1987–2017. *Source:* Macadamia Society of Australia.

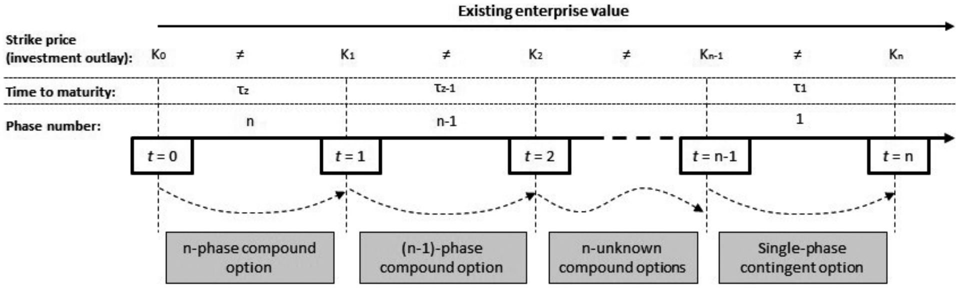

Figure 2 Valuing a sequential investment as a compound option.

expenses and labour. Additional costs of $500–$1,500 per hectare are incurred during harvesting which includes costs related to dehusking, drying and storage. U.S. and Australian growers incur greater production costs mainly from labour-related expenses and higher capital usage while growers in southern Africa experience costs at the lower end of these ranges coupled with lower capital usage.

3. Measuring adaptability

In theory, the enterprise value of an agricultural operation is comprised of the present value of expected future returns plus the option value of future investment opportunities. A farm that maintains the flexibility to alter production in the future will be worth more than an identical farm that cannot. The Faustmann model, also known as the Faustmann–Ohlin theorem, is cited in forestry applications to address this problem. Their approach finds that the net present value (NPV) is maximised when the marginal benefit of waiting equals the marginal opportunity cost of delaying the harvest (i.e., interest forgone on current profit) plus the marginal opportunity cost of delaying future harvests (i.e., interest forgone on all future profits). Both Englin and Callaway (1993) and Seidl *et al.* (2011) applied a variant of a vulnerability assessment approach using the Faustmann model to construct a multicriteria decision analysis for assessing optimal forest rotations under changing environmental conditions. However, this more advanced variant of the model makes a number of simplifying assumptions and only serves as an approximation for finding the optimal rotation cycle (Erickson *et al.* 1999). Some of the assumptions include perfect growth renewability in the form of a constant growth function across all future planning periods, an infinite investment horizon and a functional form for forest regrowth under natural regeneration. These assumptions limit the applicability of such models to tree crops that produce output through the life of the tree under a range of stochastic price and volume realisations.

In early literature, Hertzler (1991), Dixit and Pindyck (1994) and Caballero and Pindyck (1996) derived a generalised geometric Brownian motion (GBM) model to assess the optimal time for a company's decision to invest. Purvis *et al.* (1995) analyse technology adoption for a free-stall dairy housing given irreversibility and uncertainty in response to environmental policies. They compared expected returns from new technology with prevailing technology assuming returns are influenced by a combination of two independent stochastic factors: milk production; and feed costs. An extension of this approach combined with high sunk costs was conducted by Price and Wetzstein (1999) who analyse the market for perennial crops. Khanna *et al.* (2000) examined the use of real options to understand the impact of price uncertainty combined with declining fixed costs on the optimal timing of investment in site-specific crop management (SSCM). They demonstrated that delayed investment for several years is optimal unless average soil quality and fertility remains are high. These studies are limited, however, by the fact that optimisation is solved at a single investment point only, whereas most farmers encounter many investment points throughout the stewardship of an enterprise.

To address this, other scholars have made incremental improvements to previous models. Odening *et al.* (2005) used real options for multiple investments in hog production. Fenichel *et al.* (2008) used a similar approach for precautionary fisheries management, and Musshoff (2012) demonstrated a sequential real options approach to investigate short rotation coppice in Germany. These studies, however, do not explicitly model the compound option effect necessary for sequential options, where future investment decisions are heavily dependent on the valuation changes caused by previous decisions.

In other research, Schwartz and Moon (2001) and Brach and Paxson (2001) numerically solved a continuous-time model to estimate the value of research and development (R&D) projects in pharmaceuticals. Others followed such as Kellogg and Charnes (2000), Milne and Whalley (2000), Carey and Zilberman (2002) and Ilan and Strange (1998). Each of these approaches assumed total expenses are known with certainty. Schwartz (2004) used a simulation approach to value patents and accounted for uncertainty in completion costs, cash flows and the potential for investment-ending events. Errais and Sadowsky (2005) introduce a general discrete-time dynamic framework to value pilot investments that reduce idiosyncratic uncertainty with respect to the final cost of a project. They use a dynamic programming algorithm that relies on the independence of increments in state variables in an incomplete market. Song *et al.* (2011) apply a real options approach for energy crops but assume that for agricultural land, a farmer can switch between different uses. This two-way decision is not strictly relevant for a horticultural tree crop like macadamias which are planted in specific locations to take advantage of climate conditions and switching to another equally valuable crop is not typically feasible.

However, it is clear that the transitional years during which a grower waits for newly grafted or planted cultivars to mature are irreversible. Forgone revenue cannot be recovered and the grower does not receive the salvage value of spent capital from another source during the transition. The level of a grower's perception of uncertainty about future price premiums will largely dictate the duration of the delay of an investment while accumulating more information.

A simple example illustrates the embedded options nature of the investment alternatives available to a grower. Consider the complete replacement of new, high volume and high-quality macadamia cultivars with an initial investment of \$200/tree and an expected present value of future cash flows using a risk-adjusted discount rate equal to \$175/tree. The NPV of this investment would simply equal negative \$25/tree and the decision would be to not invest. Now consider the value of the option to split the replacement process at some future date once better information becomes available on the output of the new cultivars versus the old cultivars. For simplicity, we could assume the replacement may turn out to be either a good investment or a bad one. A further investment may require \$600/tree in, say, three years' time and could produce an expected present value of future cash flows equal to \$500/tree at that time. This would be equivalent to a value of \$290/tree today (assuming 20 per cent return on, and of, capital). Using the NPV metric, the additional investment in three years' time would be valued at negative \$100/tree. But since future cash flows are uncertain, the value of the cash flows of \$290/tree can be viewed as stock that stochastically evolves over time with random movements governed by the historical standard deviation. If the expected value of cash flows in three years' time is greater than \$600/tree then the option to invest would proceed. If it is less than \$600/tree then no further investment should take place. If there are further embedded options present (i.e., to split the farm into greater segments for replacement), then the option to invest resembles an American-style call option exercisable at some point beyond three years with an exercise price of \$600/tree.

Valuing this option using a standard Black–Scholes approach (a gross simplification of the model adopted here) would equal to \$35/tree, which produces an overall NPV of negative \$30/tree plus \$35/tree which equals \$5/tree. Reserving the right to switch to multiple cultivars is an attractive investment, even though the NPV suggests such an investment is negative.

A grower maintains flexibility to:

1. defer the conversion to newer cultivars;
2. permanently abandon cultivar conversion by foregoing subsequent planned investment outlays;
3. vary the rate of conversion by adjusting investment outlays and income forgone; and
4. switch the land from current to an alternative use (e.g., other profitable land-use activities or salvage value including farm equipment).

The option to defer is valued as the aggregation of a series of American call options on the project, with an exercise price equal to the necessary investment outlays. The option to permanently abandon the conversion process during the transition is valued as a compound call option on the entire transition process itself. The option to vary the rate of conversion can be valued as a European put option on discrete parts of the transition process, with an exercise price equal to the potential cost savings. The option to switch use can be valued as an American put option on the transition process, with an exercise price equal to the value of the best alternative use of the land. We assume this to approximate its salvage value as grazing land.

The replacement of macadamia cultivars represents an investment opportunity containing multiple real options. The conversion from older to newer cultivars is represented as a series of investment outlays at specific times on a portion of the farm while maintaining some minimum level of production from the existing orchard to maintain income for the grower. An initial outlay of K_1 is followed by subsequent outlays of $K_2, K_3,\ldots,K_n$ which generate cash flows upon reaching maturity that follows each sequential investment outlay.

We therefore appraise the sequential replacement of cultivars using a multicompound options approach that captures the crucial decisions available to growers evaluating the transition to more resilient and better yielding varieties. One prior approach includes Agliardi and Agliardi (2005) who derive an approximate pricing formula for the sequential investment in R&D firms; however, their approximation neglects the valuation of the option to delay or abandon during each phase of the transition. In a similar study, Trigeorgis (1993) uses a generic project to numerically approximate the option to defer, abandon, contract, expand, and switch use. This approach examines flexibility at each step in the transition such that multicompound options can be written on existing compound options. Importantly, Trigeorgis (1993) showed that the value of an option in the presence of other options may differ from its value in isolation. Options tend to be more additive when the options involved are of opposite types, possible exercise times are close together and the options are well out of the money. Our approach minimises these errors due to the fact that each decision is an in-the-money American-style call option that forces distinct gaps between investment timing. Our approach therefore extends the above studies to a more general representation that caters for the sequential nature to switch variable proportions of a farm at any time.

4. Methodology

A farm operation has two choices when faced with the prospect of replacing old cultivars with newer varieties: (i) cease operations and replace all cultivars at a single point in time; or (ii) continue partial operations coupled with a gradated cultivar replacement program at multiple time intervals. The former approach sacrifices income for several years before trees mature sufficiently to generate income while the second approach permits ongoing operations while transitioning to newer varieties. Cultivar replacement using the second approach is a sequential investment process which requires a series of two or more irreversible investment decisions. It is expected that positive cash flows are realised throughout the replacement process in order for the grower to maintain an enterprise with positive equity value to fund debt repayments and provide regular income to the grower. However, the sequential nature of the options greatly increases the complexity of the decision problem. For instance, when produce prices fail to justify partial cultivar replacement the replacement process can be abandoned. However, if prices can justify replacement opportunities, then resources can be allocated.

We commence with similar assumptions used in the Dixit (1989) contingent-claims model regarding the characteristics of the investment. We assume that the investment has an infinite life and is nondepreciating, land has an infinite life, macadamia cultivars have long lives, and depreciated equipment is restored by replacement so the depreciation necessary to maintain the investment is added to the constant operating cost. Anticipating that growers replace depreciated equipment we add depreciation to the operating cost through the model.

Option pricing in continuous time allows for closed-form solutions under certain conditions; however, in discrete time, a numerical solution is required (Cox *et al.* 1979; Rendleman and Bartter 1979). Discrete-time models can accommodate high-order state variables and require adjustments of the replicating portfolio only at discrete points in time. An appropriate discrete-time model for this problem is the binomial option pricing model that considers two distinct outcomes for the farm in each subperiod observed during the transition.

Historical data for the macadamia industry suggests that the cost of production is relatively constant in real terms for each of the four locations we examine.[1] The gross margin of production *S(p,t)* is largely a function of macadamia farm-gate prices p_t which exhibit mean reverting stochastic behaviour over time. The stochastic differential equation used to initiate the construction of the model is well known. We first assume that the farm-gate price of macadamias p_t is the main factor affecting gross margins. The gross margin *S(t)* is assumed to follow a Markovian process defined by:

$$S(t) = S_0 e^{X(t)}, \tag{1}$$

where $X(t) = \sigma B(t) + \eta(m - \mu)t$ is a geometric Ornstein–Uhlenbeck (OU) process with long-run equilibrium m (Doob 1942), drift μ and rate of mean reversion η. $S(0) = S_0 > 0$ is the initial value. An OU process is appropriate when there is a tendency for prices to revert to some mean, and such reversion is relatively linear.

To derive the model using the above formulation, we assume macadamia farm gross margins follow the process:

$$dS = \eta S(m - \mu)dt + \sigma S dz, \tag{2}$$

where S is the gross margin of each macadamia farm, σS is the square root of the variance of S, and $dz = \varepsilon\sqrt{dt}$ is a Weiner process with ε representing a random draw from a standardised normal distribution $\varepsilon \sim N(0, 1)$.

Unlike financial options, the decision to switch a portion of a farm to new cultivars is a perpetual option which can be held indefinitely or exercised at any time. The option to switch to newer cultivars at multiple times is mathematically equivalent to a sequential compound option with exercise price equal to the net investment outlay required to perform the switch.

We apply a variation of the real option model of Cox *et al*. (1979) and Rendleman and Bartter (1979) to structure the sequential compound option payoff profile with unknown times to switch.

One approach to solving this problem is to perform a total of n steps to value the n-fold compound option. For each step, a binomial tree for each layer of the compound option is constructed. First, the binomial lattice is constructed at annual time steps to value the total enterprise out to an investment horizon of 35 years. Second, the binomial tree for the second layer of the compound option is constructed by taking into account the n-fold investment at time τ and calculating the net payoffs of the compound option to value the twofold option from $t = 0$ to τ. Third, additional layers are repeated to determine the full value of the n-fold sequential compound

[1] This assumption could be augmented by accounting for stochastic cost behaviour through time as either an additional variable or incorporated into the model replacing farm-gate prices with net return as the underlying variable.

option. This inductive approach is not robust under all circumstances due to the duration of each fold being unknown *ex ante*. In contrast, we reduce the multistep sequential replication process to that of a single-step valuation process. This allows us to construct a binomial lattice that represents the value of an n-fold compound option directly.

The replicating portfolio of single-fold option is constructed with risk-free borrowing and a long position in the enterprise. A series of uncertain investments K_1, K_2, …, K_n are then valued as a compound option by recursive application of formula using a multiplicative binomial process over multiple periods. We denote $V_{n,t}$ to be the value of the n-fold (compound) option at time t. The option to invest in new cultivars in $t = i$ can be considered an option to make an investment in the next round in $t = i + 1$, where the option is exercised only if the project value is greater than the investment K_{t+1} needed to continue the investment. If the project value declines to a point below, the cost of investment the replacement ceases until it does.

This general structure was first introduced in Copeland and Antikarov (2001) and then extended by Hauschild and Reimsbach (2015). We adapt this approach to value an unknown set of n-sequential compound options within a single binomial structure. The onefold final investment option is valued over an extended time to maturity from t_0 to t_n. This replicates the *z-n-1* fold option by forming a portfolio with a long position in the single-fold option and borrowing at the risk-free rate (Benaroch *et al.* 2006). The value of the *z-n-1* fold compound option is determined by forming a portfolio $J_{1,t}$ of a single-fold option $V_{1,t}$ in t that replicates the payoff of the option in $t + 1$ by investing in $\Delta_{1,t}$ parts of the underlying and borrowing at the risk-free rate $B_{1,t}$:

$$J_{1,t} = \Delta_{1,t} V_t + B_{1,t}. \tag{3}$$

We now value the compound option $V_{2,t}$ that represents an option on the first option $V_{1,t}$. The value of the twofold compound option is constructed by forming the portfolio $J_{2,t}$ which invests in $\Delta_{2,t}$ parts of the single-fold option V_t and borrowing $B_{2,t}$ at the risk-free rate. The value of the single-fold option V_t is replicated by $J_{1,t}$ as shown in (3). Consequently, the payoff of the twofold compound option $V_{2,t}$ can be replicated by a portfolio which consists of the partially debt-funded acquisition of the single-fold option's replicating portfolio $J_{1,t}$. Hence, the portfolio becomes:

$$J_{2,t} = \Delta_{2,t} V_{1,t} + B_{2,t} = \Delta_{2,t} J_{1,t} + B_{2,t}. \tag{4}$$

The numerically derived value of the n-fold compound option requires n steps that each contains a binomial tree to approximate the compound option value in each layer. We apply this sequentially while allowing n and therefore the underlying strike price K_n (equal to the net investment) to vary.

The replicating portfolio of the single-fold option $J_{1,t}$ is thus a linear combination of riskless borrowing B and a long position in Δ of the underlying (the enterprise). In the general case, the value of any n-fold compound option is numerically valued by forming a replicating portfolio of $\Delta^*_{n,t}$ of the underlying and risk-free borrowing $B^*_{n,t}$ where:

$$\Delta^*_{z,t} = \prod_{i=1}^{z} \Delta_{i,t}, \tag{5}$$

and

$$B^*_{n,t} = B^*_{n-1,t}\Delta^*_{n,t} + B_{n,t} = \sum_{j=1}^{n} B_{j,t} \prod_{i=j+1}^{n} \Delta_{i,t}. \tag{6}$$

The share $\Delta^*_{n,t}$ is the product of all fold-specific parts of the fold-specific underlying which is the *(i-1)*th fold compound option, or the investment project if $i = 1$. Since $0 \leq \Delta_{i,t} \leq 1$ the proportional long position in the investment to form the replicating portfolio decreases in fold number n. The borrowed amount $B^*_{n,t}$ is represented by the sum of $\Delta_{i,t}$ parts of $B^*_{n-1,t}$ and the marginal increment of additional risk-free borrowing. By increasing the number of folds of the sequential investment process, an increment $B_{n,t}$ of debt is added to partially finance the investment when forming the replicating portfolio. The proportion of irreversibly committed option premium therefore decreases which implies that the valuation of the compound option can be numerically estimated using finite differences by forming the full set of dependent replicating portfolios.

A full solution for this model could be obtained using multiple iterations of the binomial tree. The aim is to determine the optimal investment time and amount for each fold. This is made difficult by the fact that option prices can behave poorly under certain circumstances, particularly when pricing against small gross margins. The need to avoid converging on a local maximum or minimum means that the usual optimisation methods are not always robust. Instead, we use a global search algorithm to find the optimal investment time and investment amount. In line with previous research on sequential option pricing, we adopt a three-step process to this problem (Hertzler 2007; Sanderson *et al.* 2016). First, we solve the option pricing equation for all possible times and gross margins. Second, we set a constant gross margin and search for the largest corresponding option price and time. Third, we simulate the gross margin value and identify the point where the largest option price no longer exceeds the payoff function (input and investment costs). This is performed for each investment sequence over a 35-year horizon. Details on the precise valuation of sequential compound options using this method, which is an analytic version of pricing using a binomial tree, are available at the Appendix S1.

5. Results

We first consider the situation with a modest annual rate of degradation of the existing orchard (2 per cent) and initial farm-gate prices earning growers a healthy gross margin of \$11,880/ha, which represents a net return on assets of around 21 per cent for a Hawaiian grower. The grower is considering the option to switch to newer cultivars that generate a 25 per cent increase in yields at full maturity after 12 years. One option would be to transition the entire orchard at $t = 0$ and wait for seven years until the gradual increase in yields to full maturity at $t = 12$. The net margin profile depicted Figure 3a shows that the grower who opts for this strategy would receive no income for seven years but a significantly larger net margin beyond 12 years (assuming a constant gross margin). Other assumed parameters include an estimate of the rate of mean reversion and current prices. The mean reversion rate ($\eta = 0.14$; $P = 0.042$) was estimated using a linear regression of the annual change in price against observed historical prices while the mean was computed as the simple arithmetic mean ($m =$ US\$2.70). The price shift parameter used in construction the binomial tree is set to 20 per cent per annum which is calibrated to reflect historical lognormally distributed prices aligned with the Cox *et al*. (1985) approach. This is equivalent to annual price volatility (standard deviation) of X. Input data are provided in Table 1. Model calibration data are provided in Table 2.

Growers without off-farm income, alternate cropping or livestock revenues or other forms of external income support, however, will need to adopt a strategy to trade-off future gross margin gains against lost income via a phased transition. For instance, expected net margins for a grower considering options that range from a two-phase to a six-phase transition process are depicted in Figure 3b–f.

Note that the profiles in Figure 3a–f merely represent the expected net margins and not the option values for each set of inputs. As shown in each profile, while increasing the number of transitions will gradually diminish total grower margin (assuming the initial gross margin remains constant for 35 years), we observe the optimal number of transitions based on the value of the corresponding sequential compound option.

These outcomes are highly sensitive to several factors. The option value for the transition to newer cultivars can be interpreted as the grower's willingness to forego income while they wait for more information on realised rates of orchard degradation and farm-gate prices. Growers are willing to forego income because the transition process is wholly irreversible. If they enter and are wrong about future margins, they will need to rely on lower total margins from both the existing orchard and the new cultivars, or exit.

Using the global search algorithm to price the sequential options defined above, we initially compute option values for a range of deterministic sequential investments. The results in Figure 4 indicate that, for instance, a Hawaiian grower is willing to pay an option value in forgone potential

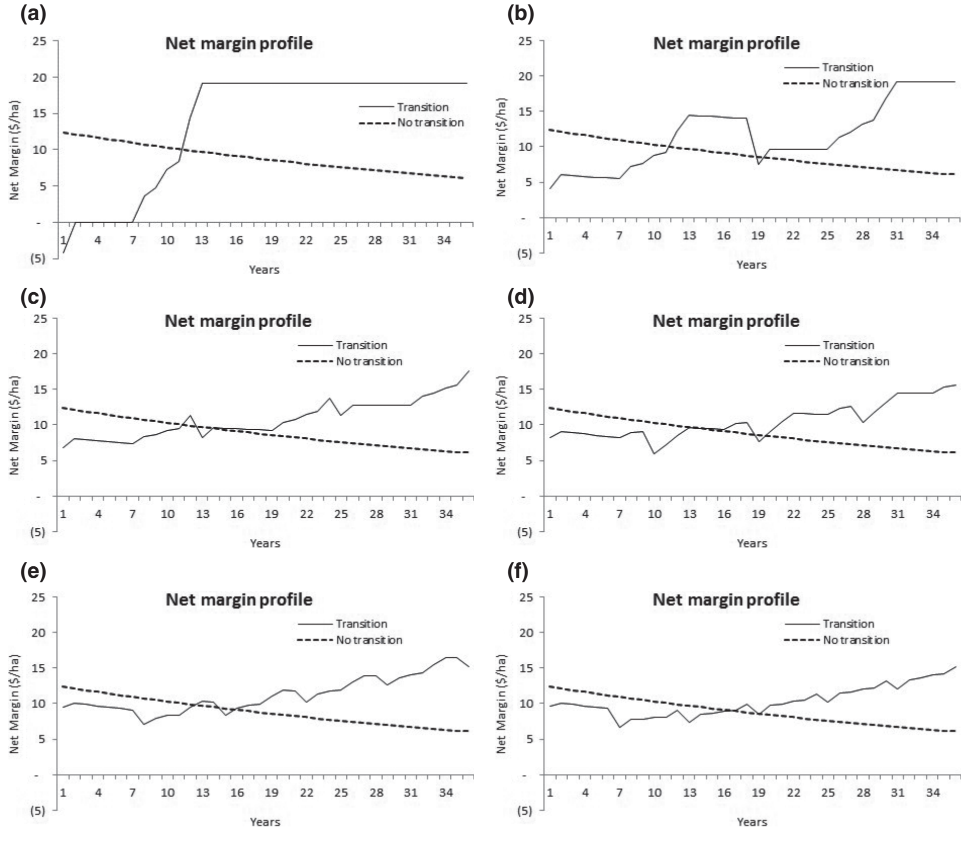

Figure 3 Net margin profiles. (a) Net margin profiles for a Hawaiian grower initiating a single-phase transition to new cultivars at $t = 0$ (initial net margin = \$10,180/ha, 2% p.a. orchard degradation, 25% yield increase using new cultivars). Total option value = \$0/ha. (b) Net margin profiles for a Hawaiian grower initiating a two-phase transition to new cultivars at $t = 0$, 18 (initial net margin = \$10,180/ha, 2% p.a. orchard degradation, 25% yield increase using new cultivars). Total option value = \$8,800/ha. (c) Net margin profiles for a Hawaiian grower initiating a three-phase transition to new cultivars at $t = 0$, 12, 24 (initial net margin = \$10,180/ha, 2% p.a. orchard degradation, 25% yield increase using new cultivars). Total option value = \$9,000/ha. (d) Net margin profiles for a Hawaiian grower initiating a four-phase transition to new cultivars at $t = 0$, 8, 16, 24 (initial net margin = \$10,180/ha, 2% p.a. orchard degradation, 14% yield increase using new cultivars). Total option value = \$9,100/ha. (e) Net margin profiles for a Hawaiian grower initiating a five-phase transition to new cultivars at $t = 0$, 7, 14, 21, 28 (initial net margin = \$10,180/ha, 2% p.a. orchard degradation, 25% yield increase using new cultivars). Total option value = \$8,710/ha. (f) Net margin profiles for a Hawaiian grower initiating a six-phase transition to new cultivars at $t = 0$, 6, 12, 18, 24, 30 (initial net margin = \$10,180/ha, 2% p.a. orchard degradation, 25% yield increase using new cultivars). Total option value = \$9,190/ha.

earnings of around \$5,900/ha while they wait to be more certain of receiving the expected gross margin as the farm transitions to newer cultivars over four investment phases. The increased frequency of investments indicates that once the Hawaiian grower observes this gross margin they will continue with the sequence of investments in order to maximise enterprise value. Investment

Table 1 Cost profile, yields and other inputs for each location, 2016–17.

	Hawaii	California	Australia	Southern Africa
Orchard size (trees)	6,000	6,000	6,000	6,000
Operating costs (/ha)	$3,000	$2,800	$3,500	$1,600
Harvest costs (/ha)	$1,425	$1,350	$1,500	$550
Average area (ha)	20	20	20	20
Average yield (kg/tree)	12	12	12	12
Yield degradation (p.a.)	2%	2%	2%	2%
New cultivar costs (/tree)	$14	$18	$20	$8
Time to initial harvest (years)	7	7	7	7
Time to full maturity (years)	12	12	12	12

Source: New South Wales Department of Primary Industries, Hawaii Agricultural Statistics Service, California Rare Fruit Growers, Inc., Southern African Macadamia Growers Association.

Table 2 Model calibration data

Model inputs	Value
Long-run average price (m)	US$2.70
Mean reversion rate (η)	0.14
P-value	(0.042†)
Price drift (μ)	0.00
Price volatility (σ)	20% pa
Time step (Δt)	1 year
Binomial tree parameters	
Up-step (u)	1.22
Down-step (d)	0.82
Total investment horizon (T)	35 years
Time interval (variable)	$\tau \in \{0, 1, 2, \ldots\}$

†Significant at a 5% confidence level.

decisions are represented in Figure 4 for each of the four locations. Growers in California, Southern Africa and Australia similarly would be willing to forgo gross margins of $6,700/ha, $5,500/ha and $3,000/ha, respectively, and commit to cultivar replacement aligned with the optimal sequence of investments. The optimal sequence is for fewer but larger investments to replace cultivars for the higher margin locations (S. Africa and Hawaii) while more frequent and lower investments are optimal for lower margin locations (California and Australia).

All else being equal, the greater the number of stages in the transition process, the lower the initial investment and the smaller the time between subsequent investments. However, the time to initial production and full maturity for newer cultivars remains relatively fixed at seven and 12 years, respectively, so there is a natural limit to the most effective transition rate. Too many parallel investments within the seven to 12 year maturity period sacrifices income from the existing orchard and is an inferior investment option to the decision to replace cultivars fewer times but in larger portions.

This presents the greatest value impact when the number of transitions is two (half the orchard is under transition for seven years) and six (33 per cent of the orchard remains in transition for several years at a time).

Figure 5 illustrates the option value as a function of the number of investment phases initially planned and the initial gross margin. While option prices are roughly linearly related to initial margin, the relationship between value and the initial planned number of investment phases is not quite as clear. Holding input prices steady, any increase in the volatility of prices increases the grower's value of waiting. This implies that an increase in uncertainty may also delay future investment since the greater level of uncertainty enhances the value of the option to wait for new information.

The degradation rate of the existing orchard also makes a significant difference to the rate of transition. As the rate of degradation increases the need to transition to newer cultivars becomes greater, especially for Hawaii, California and particularly Australia where gross margins are much leaner. The imperative to switch cultivars at an accelerated pace becomes greater and the grower's option value increases exponentially. Figure 6a illustrates the transition value profiles for an orchard with a modest annual degradation rate of 2 per cent, while Figure 6b illustrates the transition value profiles for an orchard with a heightened annual degradation rate of 10 per cent. After the initial investment, a grower will soon realise that an accelerated transition rate delivers a greater yield to the grower over the long term balanced by higher margins in the shorter-term before the degradation rate dominates enterprise value.

An important aspect of a grower's option to invest in cultivar replacement concerns the instability of gross margins through time, particularly when

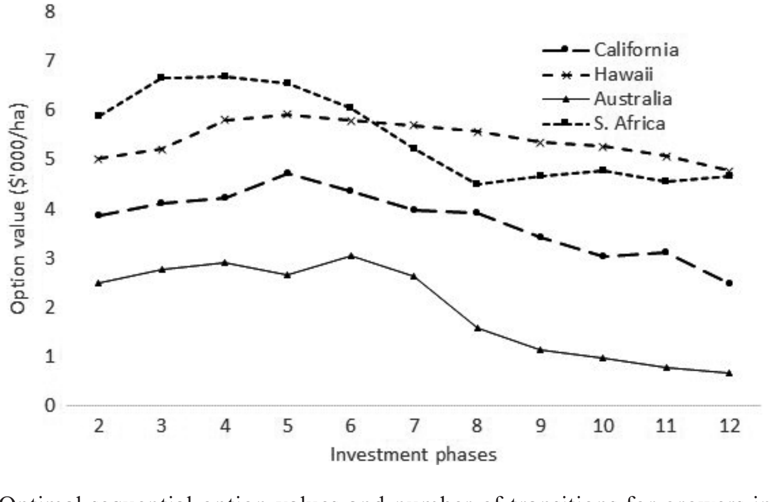

Figure 4 Optimal sequential option values and number of transitions for growers in Hawaii, California, Australia and Southern Africa assessing a phase transition to new cultivars at $t = 0$ (initial net margin = $10,180/ha, 2% p.a. orchard degradation, 25% yield increase using new cultivars).

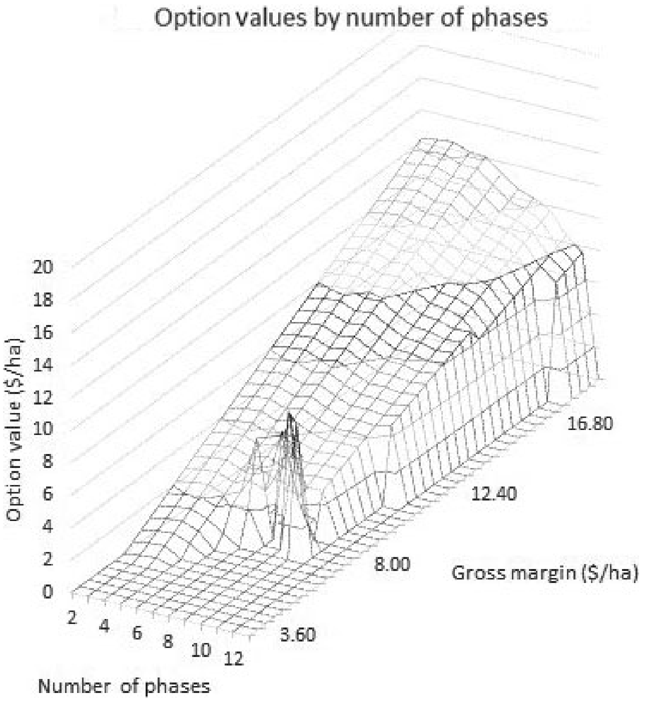

Figure 5 Sequential option values for a Hawaiian grower initiating a single-phase transition to new cultivars at $t = 0$ (initial net margin = \$12,380/ha, 2% p.a. orchard degradation, 14% yield increase using new cultivars). Total option value = \$0/ha.

margins are directly impacted by high volatility in the rate of orchard degradation. A grower exploiting a high option value as justification for delaying investment under the assumption of modest orchard degradation will suffer a significant loss in enterprise value if the degradation assumption grossly underestimates the realised rate.

Finally, Figures 7 and 8 provide results for the cumulative density functions (CDF) of the growers under a zero-degradation rate and a four per cent degradation rate respectively at the optimal transition rate for each grower location. The total gross margin CDF for each grower group were derived using 10,000 simulations of price inputs. Under a zero rate of degradation, the option to switch is felt more acutely by lower margin producers (Australia, Hawaii, California) than for a higher margin producer (S. Africa). However, as the rate of degradation in the orchard increases and future production rates from the existing orchard are likely to suffer, the option to switch becomes of great value to higher margin producers resulting in the switching behaviour becoming almost indistinguishable from lower margin producers. Increased orchard degradation rates result in a convergence of cultivar replacement strategies which may result in flow-on effects of production volumes and price as growers rapidly switch to newer cultivars to decrease the probability of incurring a negative margin over the replacement cycle.

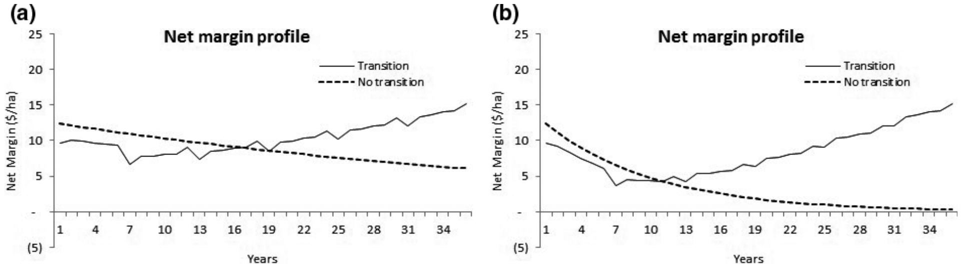

Figure 6 Net margin profiles. (a) Net margin profiles for a Hawaiian grower initiating a six-phase transition to new cultivars at t = 0, 6, 12, 18, 24, 30 with 2% p.a. orchard degradation (initial net margin = $12,380/ha, 14% yield increase using new cultivars). Total option value = $1,800/ha. (b) Net margin profiles for a Hawaiian grower initiating a six-phase transition to new cultivars at t = 0, 6, 12, 18, 24, 30 with 10% p.a. orchard degradation (initial net margin = $12,380/ha, 14% yield increase using new cultivars). Total option value = $1,800/ha.

The key results from the numerical solution in descending order of impact on enterprise value are summarised as follows:

- uncertain sequential investment timings result in a reduction in the value of waiting for new information and, consequently, the decision to invest approximates the NPV of the investment sequence;
- increases in the rate of degradation of the existing orchard and/or enhancements in yield from newer cultivars accelerates the investment sequence frequency;
- sequential investments strengthen the effect that time to invest has on investment decision; and
- increased uncertainty increases the value inherent in the decision to invest.

Given the transition to newer cultivars is irreversible, the investments made up to a certain point in time represent a grower's commitment to the transition. But the sequential investment process reduces the initial commitment and permits future investments to be deferred until more information becomes available. When the grower enters an investment phase, the option to proportionally invest is exhausted and a new option to proportionally invest is created. A grower will anticipate this circumstance before deciding to initially invest, which means the payoff function for the option to invest includes the value of the option to invest further or discontinue. The option value of the sequence of future investments is included in the initial option value.

The key problem confronting growers is that high prices coupled with modest rates of degradation of the existing orchard returns a higher enterprise value which inhibits investment in cultivar replacement. This potential circumstance faces many growers across the four locations we examined with the possible exception of Southern Africa, where growers have experienced price growth for the past ten years. If orchard degradation rates

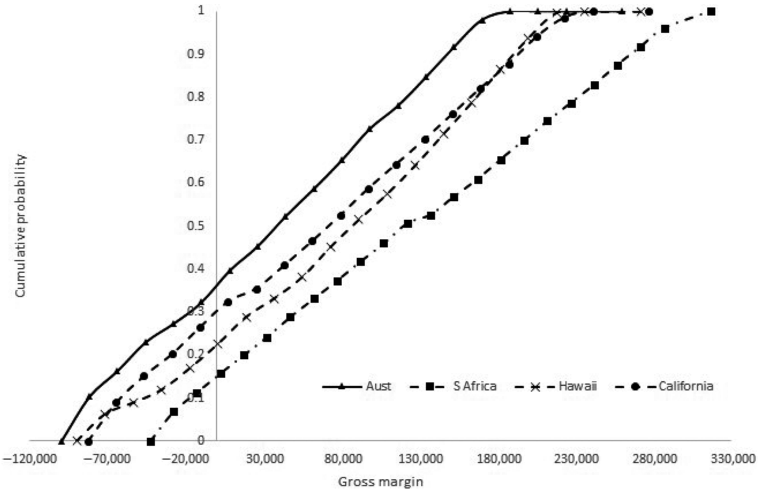

Figure 7 Cumulative density functions of growers under zero-degradation rate at the optimal transition rate for each grower location. The total gross margin CDF for each grower group were derived using 10,000 simulations of price inputs.

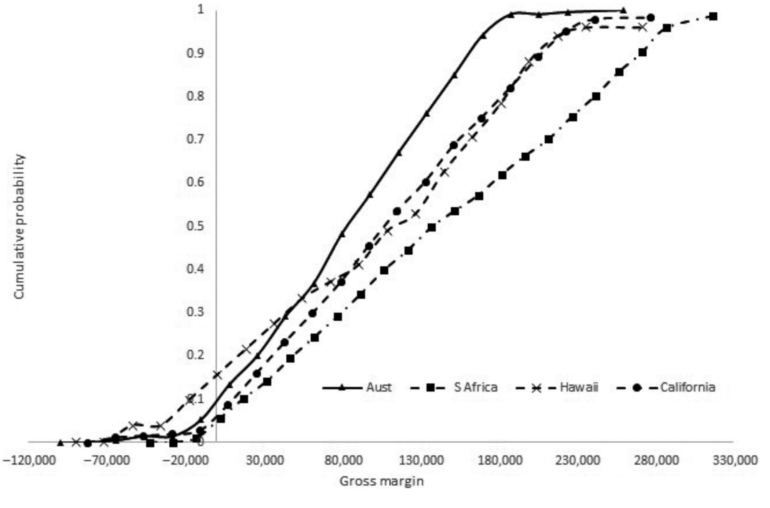

Figure 8 Cumulative density functions of growers under a 4 per cent degradation rate at the optimal transition rate for each grower location. The total gross margin CDF for each grower group were derived using 10,000 simulations of price inputs.

accelerate beyond expectations, growers may never catch up on forgone revenue and it becomes suboptimal to continue.

6. Concluding remarks and limitations

We have shown that the dual decision to: (i) switch cultivars; and (ii) selecting a proportion of an orchard to switch, is a strong function of expected price and a weak function of operating costs. The analysis shows that it is not optimal for more than one-fifth of an average orchard can be switched in any five to seven year period. This means that the adaptation cycle for macadamia farmers may extend to a long horizon of 35 years which could lie beyond the climatic cycle and cause distress on existing cultivars, impacting total production. Our model offers insight into the sensitivities growers face regarding the cultivar transition rate influenced by off-take prices and the rate of orchard degradation. Growers maintain the option to increase their transition to newer cultivars, a decision that is enhanced when experiencing high rates of orchard degradation. On the other hand, higher prices will have the opposite effect of limiting the rate of transition, even if degradation rates are increasing. This circumstance may persist until a price fall, combined with higher rates of degradation result in the farm earning negative gross margin for many years with the option to abandon macadamia production becoming valuable. In the absence of switching to newer cultivars in an optimal way as discussed in this analysis, the confluence of high prices and high rates of degradation will have significant adverse impacts on the value of macadamia production in the years ahead. This effect will be felt most acutely in lower margin locations.

This approach is subject to two minor limitations. First, there is a need for an observable and tradable underlying asset to form a replicating portfolio to practically assess values. In our case, the availability of tradeable commodities exists which alleviates the need to qualify the results. Second, numerical methods such as discrete-time binomial models assume a simplified distribution of underlying asset values. The parameters used in our example are sufficient to resemble observed market behaviour and the use of a tree-based simulation approach is justified.

The real options approach for evaluating decisions when the timing of each sequential investment is subject to uncertainty can be deployed for a range of climate change adaptation activities. The need to objectively understand trade-offs between acting sooner versus retaining the option to act later by explicitly accounting for the value of both flexibility and new information is vital for adaptation activities. Simulation and scenario testing aimed at understanding the risk of investment versus noninvestment is the main strength of the real options approach. This has direct applications for other agricultural investment decisions (e.g., irrigation), coastal adaptation, transport infrastructure and land development.

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Supporting Information

Additional Supporting Information may be found online in the Supporting Information section at the end of the article.

Appendix S1. Data and code information.