

# Climate Adaptation and Mitigation in Agriculture and Forestry: A Real Options Perspective

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## Abstract

Investments in climate change adaptation and mitigation in agriculture, livestock, and forestry entail high upfront and partially irreversible costs, long planning horizons, and multiple, interacting sources of uncertainty. These characteristics make the timing and scale of investment decisions, such as technology adoption, land-use change, and forest management, particularly sensitive to uncertainty in climate, markets, and policy. This paper reviews applications of real options analysis to climate change adaptation and mitigation in agricultural and forest systems focusing on agriculture, livestock, and forestry. It provides a structured overview of how real-options approaches have been applied to adaptation and mitigation decisions, synthesizes the treatment of uncertainty and irreversibility across studies, and identifies key research gaps and directions for future work.

KEYWORDS: Climate change adaptation; Climate change mitigation; Real-options; Uncertainty.

## 1 Introduction

Investments in climate change adaptation and mitigation in agriculture, forestry, land use, irrigation, and related water management are marked by high upfront and partially irreversible costs, long planning horizons, and multiple sources of uncertainty. Producers and land managers must decide when and how to adopt new technologies, shift land uses, or invest in infrastructure under uncertain future climatic conditions, market prices, and policy regimes, often facing decisions that are costly or impossible to reverse.

Real-options analysis (ROA) extends standard net present value (NPV) methods by explicitly valuing managerial flexibility, that is, for instance, the ability to delay, stage, expand, contract, or abandon investments as uncertainty resolves over time (Dixit and Pindyck, 1994). This framework is particularly well suited to climate-related investment decisions in agriculture and forestry, where both environmental irreversibility (e.g., deforestation, soil degradation, cumulative greenhouse gas emissions) and investment irreversibility (e.g., sunk costs in irrigation equipment, land-use conversion, or forest and perennial crop establishment) play a central role (Perrings and Brock, 2009; Mezey and Conrad, 2010).

This review is explicitly anchored to Ginbo et al. (2020), which provide the most comprehensive systematic assessment of real-options applications to climate change adaptation and mitigation up to 2018. Building on their PRISMA-based methodology and classification scheme, the present paper narrows the analytical focus to the primary sector and extends the temporal coverage to early 2026. In doing so, it integrates insights from complementary reviews in resource and environmental economics, including Mezey and Conrad (2010), Regan et al. (2015), and Wesseler and Zhao (2019), to place recent primary-sector applications within a broader conceptual and policy-oriented context.

The review is organized along three integrated dimensions: (i) the type of decision considered (incremental versus transformational), (ii) the treatment of uncertainty (implicit stochastic returns versus climate-explicit non-stationary processes), and (iii) the degree of irreversibility involved (investment, spatial, or systemic). After presenting the conceptual foundations and modeling approaches, the paper progresses from farm-level incremental adaptation to broader land-use and mitigation decisions, before concluding with policy implications and research gaps.

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Throughout the review, we use the term “primary sector” in a restricted sense, focusing exclusively on agriculture, livestock, forestry, and land-use decisions directly related to primary biological production. Extractive activities such as mining and energy production, as well as urban water supply and industrial processing, are explicitly excluded.

## **2 Conceptual foundations: irreversibility, uncertainty, and option value**

### **2.1 Irreversibility**

We emphasize two interrelated forms of irreversibility: first, environmental irreversibility arises from cumulative greenhouse gas emissions, loss of forest cover, soil degradation and desertification, or ecosystem damage that may trigger tipping points (e.g., forest dieback), after which damages are extremely costly or impossible to reverse. Second, investment irreversibility reflects sunk capital costs associated with irrigation systems, forest establishment, and land-use conversion, which cannot be fully recovered once incurred.

Real-options analysis is particularly well suited to settings in which these two forms of irreversibility coexist. Environmental irreversibility tends to favor earlier mitigation and conservation, while investment irreversibility combined with uncertainty creates incentives to delay action and preserve flexibility. ROA makes this tension explicit by framing decisions as a choice between investing now or later, rather than as a binary “now or never” problem.

### **2.2 Modeling uncertainty in climate-related decisions**

Climate-related investment decisions in agriculture, livestock, and forestry are shaped by multiple and interacting sources of uncertainty. Across the reviewed studies, three broad categories of uncertainty emerge as particularly relevant.

First, climatic uncertainty arises from variability and long-term changes in temperature, precipitation, and extreme events, which affect crop yields, pasture productivity, forest growth, and the suitability of specific locations for agricultural or forest production. In several applications, climate change enters the model through stochastic yield differentials, non-stationary productivity processes, or shifts in the distribution of gross margins across production systems.

Second, market and policy uncertainty concerns fluctuations in the prices of agricultural commodities, timber, biomass, land, and carbon, as well as uncertainty regarding the level, stability, and credibility of policy incentives such as subsidies, carbon credits, or payments for ecosystem services. Many land-use and forestry studies show that volatility in these variables plays a central role in shaping conversion thresholds and delaying adoption relative to deterministic benchmarks.

Third, behavioral and institutional uncertainty relates to risk preferences, learning about climate and market conditions, and coordination in the presence of common-pool resources such as groundwater or shared forest systems. In farm-level adaptation models, risk aversion and expectations about the resolution of uncertainty significantly affect optimal timing, while in land-use settings institutional stability influences the effectiveness of mitigation policies.

To represent these sources of uncertainty, the literature most commonly employs geometric Brownian motion (GBM) for commodity and carbon prices, arithmetic Brownian motion (ABM) for yield differentials that may take negative values, and mean-reverting (MR) processes for variables expected to fluctuate around long-run equilibria. In climate-explicit models, non-stationary stochastic processes derived from climate projections are used to capture evolving productivity conditions. Across specifications, uncertainty interacts with irreversibility to generate option values that shape investment timing and land-use dynamics.

### **2.3 Solution methods**

The choice of solution method in the reviewed studies reflects the structure of the underlying decision problem, the dimensionality of uncertainty, and the degree of irreversibility involved.

In relatively stylized settings, such as optimal harvest timing or single-threshold switching problems, analytical or semi-analytical solutions derived from continuous-time optimal stopping models are often employed. These approaches allow researchers to derive explicit investment or conversion thresholds and to highlight the role of key parameters, such as volatility, drift, and discount rates, in shaping option values.

When decisions involve discrete choices, multiple states, or two-way conversion possibilities, such as switching between agricultural and forestry land uses, binomial or multinomial lattice methods are frequently used to approximate the stochastic evolution of returns and to compute optimal policies.

More complex problems, including spatially explicit land-use change, climate-driven yield differentials, or path-dependent investment strategies, typically require numerical dynamic programming or simulation-based approaches. Monte Carlo methods and Least Squares Monte Carlo are used in cases with high-dimensional uncertainty or non-stationary climate processes, allowing researchers to incorporate projected changes in productivity or price dynamics.

Across applications in agriculture and forestry, these methods consistently reveal that incorporating uncertainty and irreversibility alters both the timing and the extent of adaptation and mitigation decisions relative to static NPV benchmarks. The specific numerical technique employed is less important than the structural insight it enables: explicitly valuing flexibility fundamentally reshapes predicted responses to climate signals and policy incentives.

### **3 Applications of Real Options to climate adaptation and mitigation in agriculture and forestry**

This section reviews real-options applications to climate adaptation and mitigation in agriculture, livestock, forestry, and related land-use decisions. For clarity of exposition, the literature is organized along three conceptual dimensions. First, we examine farm-level adaptation decisions under climate uncertainty, focusing on irrigation, production adjustments, and transformational responses such as relocation. Second, we review land-use change models relevant to climate mitigation, including conversion to bioenergy crops, carbon forestry, and conservation. Third, we consider forestry and ecosystem-service investments, where carbon markets, harvesting decisions, and climate adaptation interact within long-lived biological systems.

Across these domains, the central analytical theme remains the same: uncertainty and irreversibility jointly shape investment timing, generate option values, and often delay responses to climate signals and policy incentives relative to deterministic benchmarks.

#### **3.1 Farm-level adaptation under climate uncertainty**

##### **3.1.1 Incremental adaptation: irrigation and technology adoption**

Narita and Quaas (2014) provide a foundational real-options analysis of farm-level adaptation under climate change and climate variability, focusing on the decision to switch from rainfed to irrigated farming. Climate impacts are modeled through stochastic productivity driven by persistent climate variability, highlighting a substantial option value of waiting even when long-run climate trends make adaptation desirable. Under plausible parameter values, optimal adaptation can be delayed by several decades. A key contribution of the paper is the integration of risk preferences and common-pool resource dynamics. When irrigation relies on open-access groundwater, private and socially optimal adaptation paths diverge: depending on risk aversion and the importance of groundwater in production, uncoordinated farmers may adapt either too early or too late. While higher risk aversion tends to accelerate switching, option values linked to climate variability induce delay, generating non-monotonic adaptation patterns. The analysis underscores that private adaptation is not necessarily efficient and that policy interventions, such as risk-sharing mechanisms or coordinated resource management, may be required to align individual decisions with socially optimal adaptation timing.

Ihli et al. (2014) provide experimental evidence on the relevance of real-options reasoning for farm-level adaptation decisions under uncertainty. Using a within-subject economic experiment with farmers, the authors study the timing of investment and disinvestment in irrigation technology within an optimal stopping framework. Risk preferences are elicited independently through Holt–Laury lottery tasks and incorporated into the normative benchmarks derived from both NPV and real-options theory. The results show that

neither NPV nor ROA perfectly predicts observed behaviour, but that farmers' investment and disinvestment decisions are systematically closer to the real-options benchmark than to the NPV rule. In particular, farmers tend to postpone irreversible decisions relative to NPV predictions, consistent with a positive value of waiting, while still investing earlier than the fully optimal ROA trigger. Repeated decision rounds reveal significant learning effects: over time, farmers' behaviour converges towards the ROA benchmark in investment decisions, highlighting the role of experience in internalising option values. The study provides rare empirical support for real-options mechanisms in agricultural adaptation and shows that behavioural factors and learning interact with irreversibility to shape adaptation timing.

Sims et al. (2021) provide one of the most comprehensive climate-explicit real-options analyses of private adaptation in agriculture by integrating downscaled climate projections from multiple global circulation models into a dynamic investment framework. Focusing on water-saving irrigation investments in California's Sacramento Valley, the authors model adaptation as an irreversible switch under uncertainty in both climate-driven water availability and market conditions. Climate change enters the model through non-stationary streamflow processes derived from GCM projections under alternative emissions scenarios, allowing the authors to disentangle the effects of climate trends and climate variability on adaptation timing. A key contribution of the paper is the demonstration that climate variability does not uniformly delay adaptation. While increased variability can raise option values and delay investment under certain hydrological conditions, particularly during water shortages, it can also hasten adaptation when variability increases the likelihood of extreme scarcity. As a result, the relationship between climate variability and adaptation timing is non-monotonic and depends on how variability interacts with expected trends and market dynamics. The study shows that adaptation decisions are often more sensitive to market uncertainty than to climate variability alone, and that projections based solely on expected climate trends can systematically mispredict both the timing and likelihood of private adaptation.

Heumesser et al. (2012) analyze farm-level investment in irrigation technologies under uncertainty about future precipitation, explicitly integrating climate change into a real-options framework. Focusing on Austrian agriculture, they couple a biophysical crop-water simulation model with stochastic dynamic programming to evaluate the timing of investment in sprinkler versus water-saving drip irrigation systems. The results show that, despite higher water-use efficiency, drip irrigation is rarely adopted under private decision-making due to high sunk costs and uncertainty about future rainfall, even when water prices increase. By contrast, option values induce significant delays in irrigation investment, and adoption of drip irrigation becomes optimal only under very high equipment subsidies. The study highlights how climate-induced uncertainty and irreversibility can substantially weaken incentives for water-saving adaptation, implying that pricing policies alone may be insufficient to trigger efficient adaptation.

### 3.1.2 Switching and regime change in agricultural production

Schatzki (2003) provides one of the earliest empirical tests of real-options theory applied to land-use change under uncertainty and sunk costs. Focusing on conversion decisions from agriculture to forestry in the United States, the paper models land-use switching as an irreversible investment problem in which landowners compare stochastic returns across alternative uses while retaining the option to delay conversion. Using plot-level data, Schatzki shows that optimal conversion thresholds are substantially higher than those implied by expected net present value models, and that landowners' observed behaviour is consistent with valuing the option to wait. Greater uncertainty in returns to either agriculture or forestry significantly reduces the likelihood of conversion, while higher correlation between shocks to returns across uses lowers conversion thresholds by reducing uncertainty in relative returns. Estimated option values are economically large, ranging from roughly 7% to over 80% of the expected land asset value, providing a quantitative explanation for observed frictions and hysteresis in land-use change. The results highlight how uncertainty and irreversibility can dampen the responsiveness of land-use decisions to economic and policy incentives.

Sanderson et al. (2016) provide a climate-explicit real-options analysis of farm-level adaptation in Australian wheat production, focusing on regime switching at the margin of climatic suitability for cropping. Using a stochastic optimisation framework, the authors model transitions between wheat-dominated cropping systems and alternative production regimes, such as mixed or extensive grazing, under changing climate conditions. Climate change is represented through shifts in the distribution of gross margins driven by long-term warming and drying, combined with persistent climate variability. The analysis shows that adaptation

and transformation are governed by option values associated with irreversibility and uncertainty, leading to substantial hysteresis in regime switching. Even when climate change makes alternative production systems more attractive in expectation, farmers optimally delay switching to retain flexibility, particularly in marginal environments where returns are volatile. The results highlight that climate-driven transformation of agricultural systems is likely to occur later and more unevenly across space than suggested by static economic models, with important implications for regional adjustment and policy design.

Di Corato and Ginbo (2021) extend real-options analysis to transformational adaptation by studying the relocation of coffee farms in response to climate change. Focusing on Ethiopian smallholder coffee production, the authors model relocation as an irreversible spatial investment under uncertainty in climate-driven yield differentials between current and potential future production areas. Climate change enters the model through stochastic yield dynamics capturing long-run trends and volatility associated with changing temperature and rainfall patterns, while relocation involves high sunk establishment costs and the permanent loss of location-specific capital. The analysis shows that, even when relocation is expected to be profitable in the long run, option value considerations can induce substantial postponement, particularly under high volatility of relative yields or elevated risk aversion. By explicitly solving for optimal relocation thresholds and expected relocation times, the paper demonstrates that transformational adaptation may occur much later than suggested by static cost-benefit analysis. The authors further show that targeted subsidies reducing establishment costs can significantly accelerate relocation, but that the required policy effort rises sharply with uncertainty and risk aversion. The study provides one of the clearest real-options formulations of climate-induced farm relocation and highlights the role of policy design in overcoming option-value-driven inertia in transformational adaptation.

We then shift from farm-level adaptation to mitigation-oriented land-use change, where option values shape the pace and spatial pattern of conversion towards bioenergy, carbon forestry, and conservation.

## 3.2 Land-use change and climate mitigation

In contrast to farm-level adaptation, these models focus on irreversible land conversion decisions that directly underpin climate mitigation policies.

### 3.2.1 Conversion to energy crops and bioenergy

Song et al. (2011) analyze the conversion of agricultural land from traditional annual crops to perennial energy crops as a land-use decision under uncertainty and costly reversibility. Focusing on corn-soybean rotations and switchgrass production in the United States, they model land-use change as a two-way real-options problem in which conversion into and out of energy crops entails sunk costs. Compared with a standard NPV rule, the real-options framework predicts substantial hysteresis: farmers optimally delay conversion even when expected returns to energy crops exceed those of traditional crops, and are likewise reluctant to revert once conversion has occurred. Allowing for two-way conversion substantially alters predicted land-use dynamics relative to one-way or deterministic models, while assumptions about the underlying stochastic processes governing returns (geometric Brownian motion versus mean reversion) have a strong influence on conversion thresholds and long-run land allocation. The results imply that bioenergy policies based on static profitability measures are likely to overestimate both the speed and the extent of land conversion.

Di Corato et al. (2013) analyze the conversion of agricultural land to short-rotation energy forestry as an irreversible investment decision under uncertainty. Focusing on willow coppice plantations in Sweden, they model agricultural profits as a stochastic process while assuming relatively stable returns from energy forestry, framing the decision to switch as an optimal stopping problem. Compared with a standard NPV rule, the real-options approach predicts substantially delayed conversion due to high sunk establishment costs and the value of retaining flexibility in agricultural land use. The analysis shows that, under realistic levels of volatility in agricultural returns, private investment in energy forestry is unlikely without policy support, and that subsidies must cover a large share of establishment costs to induce conversion. The results highlight how option values can significantly dampen the response of land-use change to bioenergy and climate mitigation policies.

Regan et al. (2015) provide a general methodological contribution to land-use analysis by applying real-options analysis to the conversion of agricultural land to energy biomass production in Ireland. Modeling

biomass gross margins as an Arithmetic Brownian Motion and solving the problem using dynamic programming, they show that accounting for option values substantially raises conversion thresholds relative to NPV, implying that, at prevailing prices, immediate conversion is rarely optimal. Regan et al. (2017) extend their earlier real-options analysis by explicitly incorporating climate change into the evaluation of land-use change to biomass energy crops. Using a spatially explicit framework for semi-arid agricultural landscapes in Australia, they model uncertainty in both prices and climate-driven yields under baseline, moderate, and severe warming and drying scenarios. The results show that climate change affects conversion incentives heterogeneously across space: while biomass becomes relatively more attractive in low- and medium-rainfall areas, higher rainfall zones may experience delayed conversion due to increased yield advantages of conventional crops. Even under adverse climate scenarios, real-options analysis predicts limited and spatially concentrated biomass expansion unless biomass prices are sufficiently high, reinforcing the conclusion that climate change alone does not guarantee rapid mitigation-oriented land-use change.

Hauer et al. (2017) extend real-options analysis of land-use change by introducing spatial heterogeneity in the evaluation of agricultural-to-forestry conversion. Using a spatially explicit model calibrated to Alberta, Canada, they analyze the potential adoption of poplar energy plantations as a bioenergy feedstock under uncertainty in agricultural land values and biomass prices. The real-options framework shows that option values substantially raise the threshold for conversion relative to NPV benchmarks, leading to limited and spatially concentrated adoption on marginal lands close to processing facilities. The results indicate that even when bioenergy plantations are profitable in expectation, uncertainty and irreversibility strongly dampen land-use change, implying that large-scale biomass expansion is unlikely without sustained and targeted policy support.

### 3.2.2 Carbon forestry, agroforestry, and conservation

Behan et al. (2006) analyze the conversion of agricultural land to forestry as an irreversible land-use decision under uncertainty, motivated by climate mitigation policies promoting carbon sequestration. Using a real-options framework calibrated to Irish conditions, the authors show that farmers optimally delay conversion even when forestry is more profitable in expectation, due to sunk establishment costs and the loss of flexibility associated with irreversible land-use change. The analysis predicts a substantial waiting period, on the order of several years, before conversion becomes optimal, consistent with observed afforestation patterns. An empirical dynamic panel analysis using regional Irish data confirms these predictions, indicating that afforestation responds gradually to changes in relative profitability and that policy incentives must be sufficiently strong and persistent to overcome option-value-induced inertia.

Reeson et al. (2015) analyze the adoption of carbon forestry as a land-use change decision under uncertainty, explicitly accounting for the loss of management flexibility associated with irreversible conversion from agriculture to permanent tree planting. Using a Monte Carlo-based real-options framework calibrated to an Australian case study, they model uncertainty in both agricultural commodity prices and carbon prices, comparing mean-reverting and geometric Brownian motion processes. Their results show that, although carbon forestry may appear more profitable than agricultural alternatives under static NPV analysis, the value of retaining flexibility to switch between cropping and grazing can dominate under price uncertainty. As a result, uncertainty substantially delays the optimal timing of adoption, and uptake of carbon forestry is likely to be lower and slower than suggested by deterministic models. The study highlights the importance of accounting for both opportunity costs and option values when designing carbon-based land-use policies.

Frey et al. (2013) examine the adoption and disadoption of forestry and agroforestry systems as land-use decisions under uncertainty, explicitly accounting for managerial flexibility on both sides of the conversion choice. Focusing on the Lower Mississippi Alluvial Valley, they model agricultural, forestry, and agroforestry returns as stochastic processes and allow landowners to switch back and forth between land uses subject to conversion costs. The real-options framework predicts substantially lower adoption rates of forestry and agroforestry, reflecting the high option value of remaining in flexible annual cropping systems. While option values do not reverse the relative profitability ranking in favor of forestry, they significantly affect the timing and persistence of land-use change, highlighting that ecosystem-service-oriented land uses may be adopted later and on a smaller scale than suggested by NPV-based analyses.

Yemshanov et al. (2015) develop a spatially explicit real-options–NPV framework to assess afforestation decisions in data-poor environments, applying the model to private agricultural land in Alberta. By

incorporating the option to defer land conversion, they show that models based on NPV alone substantially overestimate both the extent and the speed of afforestation. Including option values reduces estimated land-use change elasticities to levels comparable with those obtained from econometric studies, despite the absence of detailed historical land-use data. The analysis highlights that uncertainty, irreversibility, and spatial heterogeneity jointly generate strong inertia in land-use change, reinforcing the importance of option values for realistic projections of climate mitigation through afforestation.

Abdul-Salam et al. (2022) apply a real-options framework to analyze the adoption of agroforestry systems as a mitigation strategy in agricultural landscapes. Focusing on upland livestock farming in Scotland, the authors model agroforestry adoption as a partially reversible land-use decision under uncertainty in agricultural returns and carbon prices, and compare real-options outcomes with standard capital budgeting approaches. Their results show that agroforestry adoption is substantially less likely than suggested by deterministic methods, particularly in less productive upland systems where carbon sequestration benefits are relatively low. Uncertainty and irreversibility significantly raise adoption thresholds, while upfront establishment payments are shown to increase adoption likelihood and shorten optimal rotation lengths. The study highlights the importance of policy design in overcoming option-value-induced inertia in agroforestry adoption.

Di Corato et al. (2018) analyze deforestation as an irreversible land-use decision under uncertainty in the value of forest conservation benefits. Focusing on the Brazilian Amazon, they model the trade-off between agricultural profits and uncertain ecosystem-service benefits, such as biodiversity conservation, carbon sequestration, and tourism, using a real-options framework. The analysis shows that higher expected growth in conservation benefits can significantly delay deforestation, whereas greater volatility accelerates forest conversion by increasing the likelihood of hitting the conversion threshold. By deriving the long-run average rate of deforestation, the paper demonstrates that policy instruments aimed at conservation are more effective when they stabilize, rather than merely increase, the value of ecosystem services. The results highlight how uncertainty in environmental benefits can undermine conservation outcomes even when average benefits are high.

### 3.2.3 Regenerative agriculture and carbon incentives

Stofferis et al. (2025) apply real-options analysis to the adoption of regenerative farming practices under uncertainty in carbon credit prices, focusing on mitigation incentives in agricultural systems. Modeling carbon prices as a stochastic process and treating adoption as an irreversible investment with sunk costs, the authors show that option values substantially raise adoption thresholds relative to NPV benchmarks. Even when regenerative practices are profitable in expectation, uncertainty in future carbon revenues induces a strong value of waiting, leading to delayed and incomplete adoption. The analysis further shows that adoption is highly sensitive to the design of carbon incentive schemes. Higher expected carbon prices alone are insufficient to trigger rapid uptake if price volatility remains high; instead, stable and predictable carbon revenues are required to overcome option-value-induced inertia. The results imply that mitigation policies relying on market-based carbon credits may systematically overestimate adoption of regenerative practices unless they address both the level and the volatility of incentives, reinforcing the importance of policy credibility and risk reduction for land-based climate mitigation.

## 3.3 Forestry, ecosystem services, and carbon Markets

### 3.3.1 Harvesting and Rotation Under Carbon and Timber Uncertainty

Insley (2002) provides a foundational real-options analysis of optimal forest harvest timing under price uncertainty. Modeling timber prices as a stochastic process, the paper shows that allowing for the option to delay harvest substantially increases the value of forest assets relative to the Faustmann rule. Compared with a standard NPV rule, real-options analysis predicts longer optimal rotations and greater sensitivity to uncertainty, highlighting how irreversibility and price volatility generate economically significant option values. This study establishes the core ROA mechanisms that later forestry applications build upon.

Chladná (2007) extends real-options forestry models by incorporating stochastic carbon prices alongside timber prices, explicitly linking forest management to climate mitigation incentives. Modeling timber prices as mean-reverting and carbon prices as a geometric Brownian motion, the analysis shows that rising carbon

prices and greater price volatility can substantially alter optimal rotation lengths by increasing the value of flexible harvest timing. The results demonstrate how carbon markets interact with traditional forestry returns, providing an early real-options treatment of climate policy instruments in forest management.

Tee et al. (2014) analyze forestry investment under the New Zealand Emissions Trading Scheme using a binomial real-options model with stochastic timber and carbon prices. By explicitly accounting for carbon liabilities at harvest, they show that participation in an emissions trading scheme can significantly affect optimal harvest timing and land valuation. Real-options analysis predicts delayed harvesting and higher forest values relative to NPV benchmarks, particularly when carbon prices are volatile. The paper highlights how policy-induced carbon price uncertainty shapes forestry decisions and mitigation outcomes.

### **3.3.2 Methodological extensions in forestry investment**

Milanesi et al. (2014) introduce a fuzzy real-options approach to forestry investment decisions, allowing for ambiguity in future payoffs rather than precise probability distributions. Applying the model to forest investments, they show that incorporating ambiguity further increases the value of waiting relative to standard ROA and NPV analyses. Although methodological in nature, the paper reinforces the general conclusion that uncertainty, especially when probabilities are imprecise, can significantly delay irreversible forestry investments relevant for climate mitigation.

### **3.3.3 Carbon market risk and policy design**

Matsuhashi et al. (2008) apply real-options analysis to Clean Development Mechanism forestry projects, focusing on the management of regulatory and market risk in carbon offset investments. The study shows that uncertainty over carbon credit prices and institutional arrangements creates substantial option values that delay project initiation. Fixed-price contracts or guaranteed purchase agreements are shown to reduce risk and accelerate investment, illustrating how policy design can mitigate option-value-induced inertia in climate mitigation projects.

### **3.3.4 Climate adaptation in forestry**

Schou et al. (2015) analyze forest harvest and regeneration decisions under climate change-related uncertainty, explicitly modeling managers' subjective beliefs and learning. Using a real-options framework, they show that expectations about when climate uncertainty will be resolved critically affect optimal harvest timing and species choice. When forest managers expect uncertainty to persist for a long period, decisions rely more heavily on ex ante assessments and may become suboptimal relative to cases with faster learning. The study highlights how beliefs and learning dynamics interact with irreversibility in climate adaptation within forestry.

Dittrich et al. (2019) apply a real-options framework to afforestation as an ecosystem-based adaptation measure for flood risk management. Using a case study from the Scottish Borders, the authors model afforestation as a sequential and partially irreversible investment aimed at maintaining a given flood protection standard under non-stationary climate conditions. Climate uncertainty is represented through probabilistic rainfall projections derived from UK climate data, and learning is captured through staged planting decisions over time. The results show that flexible afforestation strategies can substantially reduce expected costs relative to worst-case, inflexible strategies, highlighting the value of learning under climate uncertainty. At the same time, high maintenance and opportunity costs may limit the attractiveness of afforestation when flood damages are relatively low, underscoring the importance of cost structure and policy design in ecosystem-based adaptation.

Sauter et al. (2016) provide experimental evidence comparing Faustmann and real-options predictions for forest harvesting decisions. Using laboratory experiments with forestry professionals and students, they show that observed harvesting behavior is closer to real-options benchmarks than to Faustmann rules, particularly under uncertainty. Participants systematically delay harvest relative to deterministic predictions, consistent with valuing the option to wait. The results offer rare behavioral validation of real-options mechanisms in forestry and support the relevance of ROA for understanding real-world responses to climate and market uncertainty.

## 4 Cross-cutting patterns across agriculture and forestry applications

Although the reviewed studies span diverse decision contexts, ranging from farm-level irrigation investment to land-use change, carbon forestry, and regenerative agriculture, they reveal a set of remarkably consistent patterns.

First, uncertainty and irreversibility systematically raise investment and conversion thresholds relative to NPV benchmarks. Whether the decision concerns irrigation adoption, regime switching, afforestation, biomass expansion, or forest harvesting, incorporating option values leads to delayed action and lower responsiveness to price or policy signals than deterministic models would predict. This finding holds across both adaptation and mitigation contexts.

Second, climate change rarely induces immediate transformation in isolation. In adaptation settings, climate variability and non-stationarity interact with market uncertainty in complex, often non-monotonic ways. In mitigation-oriented land-use change, climate policy instruments, such as carbon prices or bioenergy incentives, must be sufficiently strong and stable to overcome the value of waiting. Across cases, expected profitability alone is insufficient to trigger rapid adjustment when decisions are irreversible.

Third, policy design and credibility play a central role. Subsidies that reduce sunk costs, stable carbon pricing regimes, and risk-sharing mechanisms can significantly lower option values and accelerate investment. Conversely, volatile or uncertain policy environments amplify delay and reduce adoption, particularly in land-use and forestry decisions where irreversibility is high.

Finally, behavioral and institutional factors matter. Risk aversion, learning, and coordination problems in common-pool resource settings can either amplify or mitigate delay. Empirical and experimental evidence suggests that decision-makers often behave in ways consistent with real-options logic, but may deviate from fully optimal thresholds due to bounded rationality or institutional constraints.

Taken together, these patterns suggest that the central contribution of real-options analysis in agriculture and forestry lies not in predicting whether adaptation or mitigation will occur, but in explaining why such transitions are typically slower, more spatially heterogeneous, and more policy-sensitive than standard cost-benefit approaches imply.

## 5 Conclusion

This review has examined the application of real options analysis to climate change adaptation and mitigation in agriculture, livestock, forestry, and related land-use decisions. Across diverse contexts, ranging from irrigation investment and production switching to afforestation, carbon forestry, and regenerative agriculture, a consistent analytical message emerges: uncertainty and irreversibility fundamentally reshape investment timing relative to static net present value benchmarks.

In adaptation settings, option values help explain why irreversible investments are frequently delayed despite expected climate pressures, producing gradual and spatially heterogeneous adjustment. In mitigation-oriented land-use change, the same mechanisms generate hysteresis in conversion to biomass crops, carbon forestry, or conservation uses. Policies based solely on expected profitability tend to overestimate both the speed and the extent of transformation, particularly where sunk costs are high and returns are volatile.

The reviewed literature also highlights the importance of policy design. Stable and credible carbon pricing, well-targeted subsidies that reduce establishment costs, and risk-sharing mechanisms can significantly lower option values and accelerate adoption. Conversely, volatile or uncertain policy environments amplify delay. Behavioral factors, including risk aversion and learning dynamics, further shape adaptation and mitigation timing, and empirical evidence suggests that real-world decisions often reflect option-value reasoning even when not fully optimal.

Despite substantial progress, several areas remain underdeveloped. First, richer representations of climate dynamics, including extreme events, compound risks, and non-linear productivity responses, would improve the realism of real-options models in agricultural and forest systems. Second, greater integration of empirically grounded behavioral parameters, such as heterogeneous risk preferences and evolving expectations, would enhance the predictive power of farm- and land-use-level applications. Third, multi-agent and strategic extensions remain relatively scarce. Many climate-relevant decisions involve shared resources

or landscape-level interactions, where coordination failures may compound option-value-induced inertia. Finally, closer integration between real-options modeling and institutional analysis would strengthen the policy relevance of the framework, particularly in the design of carbon markets, payments for ecosystem services, and regenerative agriculture incentives.

Overall, real options analysis provides a coherent and powerful framework for understanding why climate adaptation and mitigation in agriculture and forestry are often slower and more uneven than deterministic models suggest. By explicitly valuing flexibility under uncertainty, ROA clarifies both the economic logic of delayed adjustment and the conditions under which policy intervention can accelerate efficient transformation in land-based production systems.

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