

Defining Risk in Agricultural Land Use: A Review of Conceptual Foundations and Analytical Perspectives

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There is no single, universally accepted definition of risk. The literature presents a range of interpretations: some define risk in terms of probability or expected outcomes, while others relate it to hazards, uncertainty, or undesirable events. In several cases, risk is treated as a subjective construct, shaped by available information and human judgment. Other studies, however, approach it as an objective condition that exists independently of any observer. When risk is expressed as the combination of hazard, likelihood, and consequence, the likelihood component is often based on historical data or expert estimates. Yet this may not fully reflect changes in environmental or contextual factors, leading to overly cautious or optimistic assessments. In the agricultural sector, interest in risk analysis has grown due to its strong connection to food security and sustainability, as recognized by the Global Food Security Index (GFSI). Despite this, studies of agricultural land use rarely examine the conceptual basis of risk in detail. Therefore, this study examines how risk is defined and conceptualized in the context of agricultural land use, focusing on five types of risk: production, market, financial, institutional, and personal. Using the framework developed by Floris and Montewka (2015) for maritime transportation, the review compares definitions of risk, perspectives, and analytical approaches. The findings indicate significant variation in how risk is interpreted, suggesting that these differences partly explain the uneven effectiveness of risk management and mitigation strategies in agricultural production systems.

Keywords: risk definitions, agricultural risk, land use, review.

1. Introduction

Aven (2012) argues that there is no universally accepted definition of risk, noting that the literature offers multiple conceptualisations that differ in how probability, consequences, and uncertainty are combined. Importantly, Aven distinguishes risk as a scientific concept from risk perception, which reflects individual emotions, values, and judgments of acceptability. Risk perception is shaped by the decision-maker's knowledge base, which mediates the interpretation of uncertainty and probability.

In general terms, risk may be understood as the possibility that future actions lead to undesirable outcomes (Aven 2012). While disciplines differ in the analytical tools used to assess risk—ranging from probabilistic models to scenario-based approaches—these differences

reflect alternative measurement strategies rather than fundamentally distinct concepts.

Risk is pervasive in agriculture, yet its systematic treatment remains challenging for farmers, researchers, and policymakers. A longstanding difficulty lies in conceptual ambiguity surrounding the definition of risk, its distinction from uncertainty, and the assessment of farmers' attitudes toward risk (Hardaker 2000). In agricultural economics, risk has commonly been interpreted as (i) the chance of a bad outcome, (ii) the variability of outcomes, or (iii) uncertainty about outcomes. While these interpretations have supported extensive empirical analysis, they often rely on probabilistic assumptions that inadequately capture structural change and learning under novel conditions.

Hardaker (2016) also stated that clearly, historical frequencies can be a guide in assessing probabilities of future risks. Yet the future is necessarily more uncertain than the past. The unexpected, even the unimaginable, may occur, causing a dramatic change to the pattern of past events. Using historical frequencies to analyse risk is to assume, too often implicitly, that the process of interest is a 'stationary stochastic system', which is seldom valid.

Although Aven does not specifically examine risk in agriculture, his broader contributions to risk theory provide a useful conceptual reference. Taken together with Hardaker's work, risk can be understood as the possibility of undesirable outcomes arising from uncertain events. Both scholars highlight that, although probabilities are commonly used to estimate risk, their interpretation is often influenced by decision-makers' perceptions and judgments.

In agriculture, land use represents a key production input alongside seeds, fertilizers, machinery, water, and labour. Within the context of farmers' decision-making, land use constitutes a pre-farming decision, alongside crop mix and crop rotation (Gupta et al. 2023). Therefore, Gupta et al. (2023) identify land use as a critical pre-farming decision. Land is one of the most essential and non-substitutable resources in farming, directly shaping overall farm output. Farmers must determine how land is allocated based on seasonal conditions and demand expectations, selecting crops to maximise returns on farm assets. At the same time, land-use decisions involve considerations of farm inputs and sustainability, particularly soil health, which influence both current and future yields. This creates a significant decision-making challenge, as land is a finite resource and land-use choices carry long-term implications for agricultural production, environmental sustainability, and system resilience.

Despite extensive research on major agricultural risk types—including production, market, financial, institutional, and personal risks (Komarek et al., 2020)—land-use studies implicitly engage with risk without clearly defining it. In agricultural land-use contexts, risk therefore concerns the likelihood that land-management decisions result in adverse production, economic, or environmental

consequences, even though the methods used to evaluate such outcomes may vary.

According to the Food and Agriculture Organization (FAO), land use refers to the socioeconomic utilisation of land as a natural and economic resource, encompassing agriculture, forestry, industry, and other activities. Land-use decisions shape production systems, influence land values through expectations of future returns, and condition the sector's capacity to absorb shocks arising from environmental, economic, and institutional change. Clarifying how risk is conceptualised in agricultural land-use analysis is therefore essential for improving risk assessment, guiding policy design, and strengthening the sustainability of food systems.

2. Risk Framework

Floris and Montewka (2015) adopt the risk classification definition proposed by Aven (2012), as presented in Table 1. Floris and Montewka (2015) explain the risk definition as follows:

- Expected Value (EV): risk is the expected value of the probability of an event occurrence and the utility of the consequences.
- Probability of an (undesirable event) (P): risk is the probability of an undesirable event, or the chance of a loss.
- Objective uncertainty (OU): risk is defined as objective uncertainty, i.e., a probability distribution over an outcome range (determined through calculations or statistical data analysis).
- Uncertainty (U): risk equals uncertainty, understood as the statistical variation relative to the mean.
- Potential/possibility of a loss (PO): risk is defined as the possibility of an adverse outcome.
- Probability and scenarios/ (severity of) consequence (P&C): risk is the combination of the probability of occurrence of an event and consequences, without combining these in one unit, as in EV.
- Event or consequences (C): risk is an objective state of the world, which is considered to exist independently of an assessor.

- Consequences/damage severity+uncertainty (C&U): risk as the combination of events, consequences, and the uncertainties of these, where uncertainty is understood as an assessor's uncertainty about the occurrence of the events/consequences.
- Effect of uncertainty on objectives (ISO): risk is an effect on stated objectives (i.e., a consequence) arising from uncertainty.

Table 1. The risk framework.

Type of risks	Production	Market	Financial	Institutional	Personal
	(e.g., climate variability, pests, soil degradation)	(e.g., price volatility, input costs, demand shifts)	(e.g., policy changes, land tenure insecurity, subsidies)	(e.g., health, labour availability, knowledge constraints)	(e.g., credit access, debt, liquidity)
R = EV	Sharma et al. (2026)			Li et al. (2026)	
R = P	Sharma et al. (2026), Kemsareddy (2026)	Tapsoba and Loubier (2026)	Goswami et al. (2026)		
R = OU					
R = U			Goswami et al. (2026)		
R = PO	Sharma et al. (2026), Kikis et al. (2026), Avikasis Cohen et al. (2026), Freitas et al. (2026), Ansari et al. (2026), Schling et al. (2026)		Schling et al. (2026), Kopittke et al. (2025), Goswami et al. (2026)	Schling et al. (2026), Kopittke et al. (2025)	Schling et al. (2026), Kopittke et al. (2025)
R = P&C				Nasiri et al. (2026)	Nasiri et al. (2026)
R = C	Kikis et al. (2026), Avikasis Cohen et al. (2026), Freitas et al. (2026)				
R = C&U					
R = ISO	Sharma (2026)				

By integrating the risk framework proposed by Aven (2012), further developed by Floris and Montewka (2015), and incorporating the agricultural risk perspective articulated by Komarek et al. (2020), this study establishes a conceptual framework for understanding definitions of risk in agricultural land use.

In the agricultural sector, two primary stakeholders shape land-use decision-making: farmers and the government. The decisions made by each actor are interdependent and mutually influential. According to Adenuga et al. (2025), farmers' decisions are largely conditioned by

contextual factors, which in turn determine the effectiveness of governance instruments. Their study shows that policy effectiveness depends on how well governance measures align with these contextual conditions. In particular, farmers' behavioural determinants—such as social norms, cultural values, land tenure security, age, and remaining time in farming—play a crucial role in shaping their responses to policy interventions.

Farmers face three alternative land-use options for the land under their control—retaining, selling, or renting it—as illustrated in Figure 1. These decisions are shaped by four key

aspatial drivers: policy, economic, social, and environmental factors. Farmers' land-use choices are closely linked to personal risk, as conceptualized by Komarek et al. (2020). In this study, we examine how Komarek's risk framework informs farmers' decision-making regarding agricultural land use, with particular emphasis on the role of personal risk in shaping decisions to retain, sell, or rent farmland.

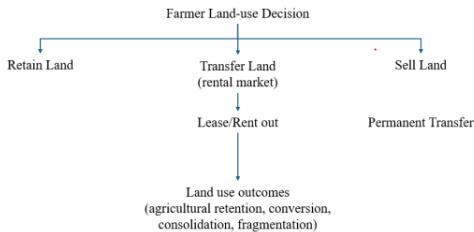


Fig.1. Farmer Land-use decisions
(Sources: the author's work)

3. Review of current interpretations and definitions

Aven has extensively examined the concept of risk across disciplines, and his work has been widely cited in the risk literature. Drawing on several publications in risk science (e.g., SRA 2018b, 2018a, 2018c, 2015), risk is commonly understood as comprising two core elements: (i) the potential consequences of an activity in relation to something of value, and (ii) the uncertainties associated with those consequences (Aven 2020). Building on this definition, Aven evaluates climate change risk in relation to statistical expected values, expressed as the product of probability (or likelihood) and impact, or through a combined assessment of both elements. He argues that recognizing the conceptual distinctions among components can improve our understanding of climate-related risks and strengthen the way such risks are communicated and managed.

In the agricultural domain, Hardaker (Hardaker 2000; Hardaker and Lien 2005; Hardaker and Lien 2010) has further developed the interpretation of risk by situating it within the context of farm decision-making and production systems. Defining risk in agriculture is particularly challenging due to the biological nature of production, the perishability of outputs, and the strong dependence on natural and socio-

economic conditions. These characteristics mean that agricultural outcomes are inherently uncertain and that risk is closely linked to management choices made under imperfect information.

Agricultural risk is also closely linked to land use, as production levels depend on both land availability and suitability. Land quality may degrade over time, and land may be reallocated to alternative uses in response to economic incentives, policy interventions, or development pressures. As a result, land-use decisions play a critical role in shaping exposure to agricultural risk. Against this background, this study focuses on establishing a coherent understanding of how risk is conceptualised in agricultural land-use contexts, providing the basis for the review of current interpretations and definitions that follows.

3.1 Production

Across the reviewed literature, production risk in agriculture is rarely defined through a single, standalone definition. Instead, risk is typically articulated through its constituent elements, including the possibility of loss (PO), undesirable events or consequences (C), and, in some cases, probability and uncertainty (P, U). In agricultural land-use contexts, production risk is most framed as the possibility of yield loss and productivity decline arising from land degradation processes, with greater emphasis placed on observable consequences and qualitative or scenario-based assessments than on formal probabilistic risk metrics.

Land is consistently identified as the most influential production input affecting agricultural output (Schling et al. 2025). While productivity is often measured as output per unit of land, this partial indicator obscures the role of complementary inputs such as labor, capital, and management practices. For smallholder systems in particular, production risk is amplified by limited access to inputs, credit constraints, and inadequate capacity to mitigate pests, diseases, and climate-related shocks.

Several studies conceptualize production risk in terms of land degradation phenomena such as soil erosion, salinization, contamination, and nutrient depletion. Sharma et al. (2026), for example, frame production risk primarily through soil erosion and land degradation, treating these

processes as undesirable events with assessable probabilities derived from rainfall patterns and erosion models. While probabilities and consequences are often discussed jointly through scenario analysis, they are rarely integrated into a single expected-value framework. Instead, uncertainty is emphasized, particularly in the economic valuation of degradation impacts.

Other studies adopt a possibility-based framing of production risk. Kikis et al. (2026) conceptualize risk as the potential for soil contamination to impair agricultural productivity and food safety, emphasizing qualitative assessment and precautionary management amid economic uncertainty. Similarly, Avikasis Cohen et al. (2026) frame soil erosion risk in Mediterranean agroecosystems as the potential for significant productivity losses and degradation of soil organic matter, relying on spatial vulnerability indicators rather than probabilistic quantification.

Production risk is also linked to nutrient management practices. Freitas et al. (2026) define risk as the conditional probability of phosphorus runoff following biosolid application, with documented environmental consequences—such as eutrophication and biodiversity loss—reinforcing the production-related risks of land-based nutrient mismanagement. In contrast, Kesamreddy et al. (2026) adopt a possibility-based definition of risk that captures both the potential for yield loss and environmental harm associated with intensive nitrogen application. This framing reflects real-world production decisions in which farmers prioritize avoiding yield loss, often by overapplying fertilizer, given the relatively small share of fertilizer costs in total production expenses.

Across studies, degraded land is consistently associated with reduced productivity and ecosystem functions due to the combined effects of climatic drivers (e.g., drought, extreme rainfall) and anthropogenic pressures (e.g., unsustainable farming practices) (Sharma et al., 2026). These studies generally assess risk using a probability–impact framework, in which the likelihood of adverse climatic events is linked to potential production losses. However, Aven (2020) and Aven and Renn (2015) caution against an overreliance on statistical expected values, noting that risk is more accurately conceptualized as comprising both the potential consequences of

an activity and the uncertainties associated with those consequences. Focusing solely on probability \times impact may conceal important aspects of risk and uncertainty. As noted by Aven (2012), risk perception is further shaped by the decision-maker's knowledge base, which mediates the interpretation of uncertainty and probability in decision-making. While Sharma et al. (2026) primarily apply the probability–impact framework because it is relevant to climate-related production risks, awareness of the broader conceptualization of risk—distinguishing between consequences and uncertainties—provides a more complete understanding of agricultural land-use risk. However, a detailed discussion of this perspective is beyond the scope of this paper.

Production risk in agricultural land use is predominantly conceptualized as the possibility of loss arising from land degradation and management decisions, rather than as a formally quantified expected value. This emphasis on consequences, uncertainty, and vulnerability reflects the complex and context-dependent nature of agricultural production systems. Production risk is frequently operationalised as the possibility of adverse outcomes—such as crop failure, yield loss, and soil degradation—arising from exposure to climate hazards, including drought, erratic rainfall, floods, and temperature extremes (Sharma et al. 2026; Avikasis Cohen et al. 2026; Ansari et al., 2025).

3.2. Financial

Financial risk in agricultural land use is most conceptualized through credit-related mechanisms, particularly the likelihood of loan default. Goswami et al. (2026) frame financial risk in agriculture primarily as credit risk, defined as the probability of an undesirable event—namely borrower default—shaped by geographic, environmental, and socioeconomic conditions. A key contribution of their study is the identification of land-use patterns as critical yet underutilised site-specific risk factors in financial risk assessment.

Based on a survey of 66 financial research providers, Goswami et al. (2026) show that environmental risk evaluations largely rely on aggregated indicators such as greenhouse gas emissions, water and climate risks, and air pollution, while neglecting localised land-use

attributes, including soil health, land degradation, and over-exploitation risks. This limited integration of land-use information constrains the accuracy of credit risk evaluation, despite its relevance for assessing farm productivity and repayment capacity.

Conceptually, financial risk is articulated through multiple dimensions. Credit risk is treated as a probabilistic outcome (P), with empirical evidence indicating higher default probabilities among rural micro-borrowers due to monitoring constraints. Financial risk is also framed as the possibility of loss (PO) arising from environmental shocks, such as droughts, floods, and other natural disasters, that disrupt production and undermine income stability. Uncertainty plays a central role: objective uncertainty (OU) is addressed through AI and machine learning models—such as Bayesian decision-making frameworks and deep neural networks—that infer default risk from historical data. In contrast, broader uncertainty (U) arises from climate variability and weather extremes, which affect yields and farm incomes.

Scenario–consequence relationships further structure financial risk. For example, water scarcity in arid regions constrains production potential. It increases default risk, while spatial variation in soil fertility in hilly areas affects profitability through interactions with slope and land characteristics. The Agricultural Land Suitability Evaluator (ALSE) proposed by Goswami et al. (2026) implicitly links land suitability to anticipated farm income and loan viability, thereby supporting expected-value reasoning in credit decisions.

Beyond credit risk, land tenure and market institutions shape financial exposure. Schling et al. (2026) highlight collateral risk, showing that secure land ownership facilitates access to credit by enabling land to be used as collateral, whereas tenure insecurity increases the risk of capital loss and foregone investment opportunities. In land markets, insecure tenure also raises transaction costs, increasing financial risk by limiting efficient land reallocation through rental or transfer mechanisms.

Kopitke et al. (2025) further broaden the financial risk perspective by identifying cost–benefit pressures, price-structure disadvantages, and externalities as key drivers. However, their analysis does not explicitly link these risks to any

of the nine risk definitions discussed in the literature, making it difficult to determine which conceptual framework most closely aligns with the risks they describe. Farmers' incentives to minimise costs often discourage adoption of soil-conserving practices when labour or implementation costs exceed short-term gains. At the same time, market pricing structures frequently prevent producers from recovering the additional costs associated with sustainable practices, while environmental externalities lead to systematic undervaluation of land and soil resources.

These studies show that financial risk in agricultural land use is not limited to loan default but also encompasses interconnected risks related to land suitability, tenure security, market institutions, and environmental externalities. However, despite the central role of land in shaping financial outcomes, land-use characteristics remain insufficiently integrated into formal financial risk assessment frameworks.

3.3. Market

Several cost-related variables serve as key sources of uncertainty in agricultural production, including input costs (e.g., fuel consumption and labor use), output prices subject to market fluctuations, price correlations (such as the dependence of wheat and fertilizer prices on oil prices), and long-term production costs that may evolve as soil quality changes (Tapsoba and Loubier 2026).

In this study, risk is explicitly defined as the statistical probability of financial loss or economic undesirability, operationalized through Net Present Value (NPV) outcomes. Specifically, risk refers to the probability that adopting Conservation Agriculture (CA) results in a negative private benefit—that is, a negative NPV from the farmer's perspective—indicating that the practice is unprofitable for the individual decision-maker.

The analytical framework evaluates both private and public benefits of CA by incorporating environmental externalities and addressing the risks and uncertainties associated with CA adoption through a stochastic cost–benefit analysis. In this context, risk is understood as situations in which the probabilities of outcomes (e.g., financial loss) are known or can be estimated. In contrast, uncertainty refers to

situations in which these probabilities are not well-defined. For example, production-related risks—such as yield fluctuations driven by known weather patterns or input price volatility—are distinguished from uncertainties—such as unforeseen regulatory changes or unknown environmental impacts. However, the authors attribute both production-related risks and uncertainties to variability in pesticide and fertilizer costs, labor requirements for mechanical cropping, machinery expenses, and irrigation inputs, without explicitly differentiating between the two.

3.4 Institutional

Institutional risk in agricultural land use arises from socio-economic, legal, and policy structures that shape farmers' incentives, constraints, and exposure to loss. A central institutional risk identified in the literature is land tenure insecurity, which fundamentally alters land-use decisions and increases the likelihood of land degradation.

Kopittke et al. (2025) identify land tenure security (LTS) and land pressure as key institutional drivers of soil degradation. Insecure tenure discourages long-term investment in soil conservation by weakening farmers' expectations of capturing future benefits. As a result, decision-making tends to prioritise short-term production gains over sustainable land management, increasing the probability of undesirable outcomes such as erosion, nutrient depletion, and declining soil organic matter. Empirical evidence shows that owner-operated land exhibits better soil biochemical properties than leased land, indicating measurable consequences of tenure insecurity.

Land pressure further amplifies institutional risk by forcing agricultural expansion onto marginal lands. Population growth and land fragmentation—particularly in low- and lower-middle-income countries—reduce average farm size and intensify cultivation on environmentally vulnerable areas, accelerating soil degradation. Within this framework, risk is implicitly defined as the probability of an undesirable outcome, as evidenced by reduced adoption of erosion-control measures, increased nutrient mining, and declining soil quality.

Institutional risk also manifests through legal and market mechanisms. Schling et al.

(2026) show that secure land ownership reduces the risk of legal land conflicts, lowers transaction costs, and facilitates land transfers through rental markets. These mechanisms enable more efficient allocation of land to productive users and encourage investment in land-improving infrastructure such as fencing and irrigation. Conversely, tenure insecurity exposes farmers to the possibility of losing land through disputes or dispossession, representing a fundamental potential loss (PO) that constrains investment and productivity, particularly among smallholder and impoverished family farmers.

Policy frameworks play a dual role in shaping institutional risk. While well-designed policies can encourage sustainable land management, poorly aligned interventions—such as input subsidies, population policies, or distorted credit incentives—may inadvertently increase land degradation by promoting intensive or inappropriate land use (Kopittke et al. 2025). These institutional failures create systemic risks that extend beyond individual farms.

Broader governance and regulatory risks are illustrated by Li et al. (2026), who analyse ecosystem service degradation risks arising from land-use change under alternative policy scenarios. Their study explicitly defines risk as the expected value of loss, combining scenario probabilities with ecosystem service value losses. Although focused on urban spatial planning rather than agriculture per se, the framework demonstrates how institutional coordination failures and inconsistent land-use policies can generate high-risk outcomes for cropland and ecological functions.

Institutional risk is also shaped indirectly through behavioural pathways. Nasiri et al. (2026) show that regulatory measures—such as taxation, penalties, and awareness campaigns—do not pose risks in themselves but instead modify psychological drivers that influence land conversion decisions. These policies alter the probability and perceived severity of undesirable outcomes, thereby reshaping the likelihood of land sale or conversion. This indirect risk pathway highlights the role of institutions in mediating behaviour through incentives, norms, and perceptions rather than through direct physical impacts.

Institutional risk in agricultural land use is best understood as the possibility of loss arising

from insecure tenure, legal conflict, policy misalignment, and governance failures. These risks increase the likelihood of land degradation, constrain investment, and weaken the institutional conditions necessary for sustainable land management.

3.5 Personal

Personal risk in agricultural land use arises from individual farmers' socio-economic conditions, behavioral responses, and perceptions that shape decision-making under constraints. Kopittke et al. (2025) highlight poverty as a central driver of soil degradation, particularly in developing countries where more than 75% of the global extreme poor reside in rural areas and depend on agriculture for subsistence. Under conditions of extreme poverty, farmers often cultivate marginal lands and prioritise short-term survival needs over long-term soil conservation, increasing the likelihood of land degradation.

The relationship between economic well-being and land degradation is bidirectional. Lower incomes constrain farmers' capacity to invest in soil conservation, while soil degradation further entrenches poverty by reducing productivity and livelihood resilience. Although higher economic well-being is generally associated with improved conservation outcomes, Kopittke et al. (2025) emphasize that behavioral, institutional, and contextual factors mediate this relationship, such that even wealthier farmers may engage in soil-degrading practices when incentives or tenure security are lacking. In this study, personal risk is not treated as a formally quantified probability but as a causal mechanism that increases the likelihood of undesirable outcomes. Financial pressures, institutional constraints, and personal circumstances—such as poverty and immediate consumption needs—are described as interacting drivers shaping rational yet short-sighted land-use decisions. These pathways reflect conceptual causality rather than stochastic risk modelling.

Personal risk is also evident in labour allocation and efficiency outcomes. Schling et al. (2026) show that tenure insecurity constrains farmers' ability to make productive investments—such as irrigation infrastructure or fencing—that would otherwise reduce production risk and enable more efficient use of labour and other inputs. Socioeconomic characteristics,

including income and education, simultaneously influence farmers' tenure decisions and their technical efficiency, creating interdependencies between personal attributes and production outcomes. When tenure is insecure, farmers risk losing returns on labour investments, leading to suboptimal labour allocation, reduced productivity, and foregone household income.

Behavioral and perceptual dimensions of personal risk are explicitly modelled by Nasiri et al. (2026), who incorporate heterogeneity in farmers' risk perceptions and moral norms into an agent-based framework. Risk is operationalised through psychological constructs such as Outcome Expectation, Perception of Others' Behavior, Self-Efficacy, and Moral Norms, as well as through Perceived Susceptibility (probability) and Perceived Severity (consequence). These parameters jointly determine the calculated probability of land-use conversion, an undesirable event that results in the loss of ecosystem service values when agricultural land is converted to urban or residential uses.

Personal risk in agricultural land use is best understood as the possibility of loss arising from constrained decision-making, behavioral responses, and perceived threats under conditions of poverty, insecurity, and limited alternatives. These risks operate through farmers' choices regarding labour allocation, investment, and land management, shaping land-use outcomes even in the absence of formal probabilistic risk assessment.

4. Conclusion

Five principal categories of risk in agriculture—production, market, financial, institutional, and personal—correspond to Aven's definitions of risk as the possibility of loss (P), uncertainty (U), the possibility of an unfortunate occurrence (PO), and the effect of uncertainty on objectives (ISO).

Production risk in agricultural land use is primarily the potential for loss arising from land degradation, management practices, and exposure to climate-related hazards such as droughts, floods, and temperature extremes. This conceptualization emphasizes consequences and uncertainty rather than formally quantified expected values. Financial risk is analyzed using both probabilistic and uncertainty-based perspectives. Credit risk is typically regarded as a

probabilistic outcome (P), whereas income and viability risks are considered possibilities of loss (PO) arising from environmental shocks and market instability. Broader uncertainty (U), particularly from climate variability, further affects financial performance and decision-making.

Institutional risk refers to the possibility of loss resulting from insecure land tenure, policy inconsistency, legal conflicts, and governance failures. Such institutional conditions introduce uncertainty and constrain agricultural decision-making, thereby increasing exposure to adverse outcomes. Personal risk is defined as a systemic, causal mechanism that shapes farmers' constrained decision-making under socioeconomic pressure. It is primarily associated with the possibility of loss arising from behavioral responses, perceived threats, and limited alternatives in contexts of poverty and insecurity.

This study does not engage with Aven's extensive theoretical contributions on risk and climate risk. As emphasized by Aven (2020), risk necessarily involves at least one undesirable consequence; however, consequences may also be positive, depending on perspective. System failures, for instance, may generate losses for some stakeholders while creating opportunities for others. Future research should therefore move beyond a predominantly negative framing of risk and explicitly examine positive consequences and opportunity creation, particularly in the context of agricultural land-use transitions.

This review highlights three critical gaps in current agricultural-land-use risk research. First, existing studies rarely incorporate Aven's comprehensive risk framework, which holds that risk always entails at least one undesirable consequence while acknowledging that outcomes can benefit other stakeholders. Future work should therefore move beyond a solely negative framing and explicitly analyse positive consequences and opportunity creation, especially in land-use transitions.

Second, integrating renewable energy into agriculture offers a tangible opportunity. Agrivoltaics systems—first proposed by Goetzberger and Zastrow (1981) (Pelczar 2025) and now occupying roughly 20% of cultivated land—simultaneously generate electricity and support crop production, alleviating land-use competition and enriching the risk landscape with

physical, economic, and social dimensions (Heinrichs et al. 2026).

Third, while AI and mechanistic crop models promise to reduce agricultural risk, their reliability is constrained by uneven data quality, operational uncertainties, and ethical concerns over equitable data access (Schweng et al. 2026; Sreeram et al. 2026; Zheng et al. 2026; Elbitar et al. 2026). Addressing these challenges calls for interpretable, co-designed AI tools, robust cost-benefit analyses, and long-term governance frameworks.

Deng et al. (2026) explained that the agricultural land use system (ALUS) management supports the scientific and rational use of agricultural land resources to achieve sustainable agricultural development, particularly in the context of climate change, emission risks, and environmental risks. In the new development stage, integrating data-driven techniques with ALUS management has the potential to revolutionize various aspects of agricultural land use, including forecasting, monitoring, decision-making, and optimization, thereby providing new solutions for the low-carbon, green, and efficient development of ALUS.

In the context of smart agriculture, as part of its future scope, Arputharaj and Karunanithy (2026) explained that the approach reduces soil chemical contamination through precision monitoring of soil quality and crop health, thereby promoting SDG 15 (Life on Land). The technology optimizes the use of pesticides and water, thereby promoting eco-friendly crop production with minimal chemical residues. It supports SDG 12 (Responsible consumption and Production). By increasing crop yields and quality and making food more affordable, this supports SDG-2 (Zero Hunger). The system minimizes the excessive use of chemical pesticides, ensures the availability of healthier food, and safeguards human health and well-being. Thus, it contributes to SDG 3 (Good health and well-being). Through precision farming, the system reduces production costs and creates opportunities for sustainable economic growth, thereby aligning with SDG 8 (Decent Work and Economic Growth).

By integrating Aven's risk taxonomy with emerging agrivoltaics and AI technologies, scholars can develop more balanced, opportunity-

oriented risk assessments that support sustainable, low-carbon agricultural systems.

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