Complementing Carbon Credits from Forest-Related Activities with Biodiversity Insurance and Resilience Value
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Abstract: Carbon credits are a core component of many national and organizational climate strategies. Financing and delivering forest-related carbon credits involves multiple types of risk at the project level. Financial mechanisms are used to mitigate these risks for investors and project developers, and are often complemented by non-financial measures at the project site such as environmental and social safeguards or climate risk reduction measures. However, academic research has shown that safeguards and climate risk mitigation measures are not always effectively implemented in forestry carbon projects and that the specification of environmental safeguards remains underdeveloped. This text explores how ecosystem capacities can be leveraged and valued for the mitigation of, and adaptation to, environmental and climate risks in forest-based carbon projects. By enhancing biodiversity and ecosystem conditions at project sites, ecosystem capacities can complement existing mitigation and adaptation instruments through their roles in providing biodiversity insurance and contributing to ecological resilience.

1 Introduction

1.1 Nature-based Credits as a Financing Instrument to attain Nature and Climate Targets

The Paris Agreement and the Kunming-Montreal Global Biodiversity Framework set environmental targets to halt climate change and reverse biodiversity loss. Both agreements rely on the public and private sector's contributions to attain climate and nature targets, not only through implementation of measures to avoid and reduce emissions and halt further degradation of the state of nature, but also through the provision of public and private capital to finance nature-based solutions with goals such as increasing carbon sequestration, the provision of other ecosystem services and biodiversity enhancement (Deutz et al., 2020). Nature-based credits are a class of market-based financing instruments used to fund carbon avoidance or removal through nature-based carbon credits (e.g. Haya et al., 2024; West et al., 2020), or in the case of biodiversity credits, to fund biodiversity conservation and net gains (e.g. Wunder et al., 2024).

There exist voluntary and compliance markets for nature-based carbon removal and avoidance projects. An example of carbon projects involving forestry in a compliance market is California's cap-and-trade program (e.g., Badgley et al., 2022; Haya et al., 2020, 2023). Compliance markets legally mandate emission reduction targets. Credits in voluntary carbon markets are purchased by countries, companies,

and organizations either for compliance under national or regional carbon markets and targets, or, in the case of companies, as part of voluntary carbon offsetting or to improve their corporate carbon balance within their CSR commitments towards achieving net-zero targets (Axelsson et al., 2024; West et al., 2024). Programs and mechanisms to enable the financing of nature-based climate solutions, either to avoid deforestation or to enable afforestation and reforestation through carbon credits, have been developed over decades. These include the Clean Development Mechanism, followed by the Sustainable Development Mechanism under the Paris Agreement, the REDD and REDD+ initiatives to reduce deforestation and promote sustainable development, numerous national or regional offsetting markets, and the voluntary carbon market, overseen by bodies such as the Integrity Council for the Voluntary Carbon Market and the Voluntary Carbon Markets Integrity Initiative.

Carbon credits focus on financing the avoidance and removal of carbon emissions, assessed in a metric of tons of carbon dioxide equivalent. They operate on an equivalence principle making emissions, their avoidance, reduction or removal from different sources commensurable (Carton et al., 2021). This allows companies or countries to integrate carbon credits from different sources into their carbon accounting while mobilizing private and public capital to fund the implementation of nature-based climate solutions and other climate mitigation and adaptation measures. Although research has revealed a temporary decline of carbon uptake by terrestrial ecosystems during 2023 (Ke et al., 2024), their functioning as natural carbon sinks remains critical for moderating climate change (Pan et al., 2024). Specifically the conservation, restoration and sustainable management of forests of high diversity offers valuable potential to contribute to meeting global climate and biodiversity targets (Liang et al., 2016; Mo et al., 2023; Weiskopf et al., 2024) and will rely on outcome-based financing through carbon credits as one crucial financing vehicle (Swinfield et al., 2024; Wells et al., 2023). Academic literature has examined the design and functioning of carbon markets since their emergence, across both compliance and voluntary markets (Haya et al., 2023; Miltenberger et al., 2021; Pan et al., 2022; Sills et al., 2017; West et al., 2020, 2024). While institutional, regulatory, and geographical contexts of forestry-based carbon projects and programs vary (Börner et al., 2020), voluntary and compliance markets for carbon credits generated from forest projects share not only the same commodification mechanism and core requirements along the carbon credit value chain leading to credit issuance. They also face similar challenges in measuring, managing, and commodifying the risks and uncertainties inherent in the processes underlying credit generation.

2 Evaluation and design requirements for carbon projects

2.1 Financing pathway, quality and integrity requirements

The pathway of financing nature-based climate solutions through carbon credits requires investors to finance projects such as afforestation and reforestation upfront, while credits are ideally issued only after impacts have been reliably generated, measured, reported, and verified. The need for upfront investment into nature-based project implementation necessitates forecasts of future project delivery. Credit suppliers are encouraged to apply conservative estimates of impact delivery wherever uncertainties remain (Core Carbon Principles; Haya et al., 2023; Swinfield et al., 2024). A core integrity requirement in the impact evaluation of project outcomes is additionality, the principle that the impact generated by a project would not have occurred without its implementation. Assessing additionality requires establishing a counterfactual baseline against which the project's outcomes are evaluated, including the control of confounding factors (Badgley et al., 2022; Swinfield & Balmford, 2023; Swinfield et al., 2024; West et al., 2020). This additional impact must be further adjusted to account for potential leakage, unintended

consequences where protecting or restoring forests in one area leads to increased deforestation or emissions elsewhere, thereby reducing the project's net carbon benefit (Aukland et al., 2003; Schwartzman et al., 2021). Assessing additionality, leakage, and the durability of carbon storage relative to a counterfactual baseline - alongside maintaining rigorous carbon accounting on both the supply and demand sides - are core quality and integrity requirements for carbon credits and the protocols and methodologies used in their issuance (Axelsson et al., 2024; Kaplan et al., 2023; Pietracci et al., 2023). Projects are implemented and monitored over time to ensure they meet integrity and quality standards and actually deliver the intended impact. Once the impacts or outcomes have been verified by an independent third party, the project is certified, and credits are issued. Investors and companies that finance the project can then sell the issued credits on the market or use them for their own carbon accounting.

2.2 Risks and risk mitigation measures

A tension in nature-based carbon storage lies in the equivalence principle: while fossil CO_2 emissions persist in the atmosphere for hundreds to thousands of years (Archer et al., 2009; Joos et al., 2013), carbon stored in natural sinks is inherently less permanent. Forest carbon sinks, in particular, are vulnerable to human, natural, and climate-related disturbances, with climate risks expected to increase in a warming climate (Anderegg et al., 2013, 2020, 2022; Barbero et al., 2015). To manage impermanence and unforeseen losses, some carbon projects use buffer pools, which set aside a share of credits to insure against unexpected losses or reversals (Badgley et al., 2022). Yet permanence risk is only one dimension of project risk. Additional risks for investors include non-delivery of credits, overestimation of benefits, contested claims, and long time lags between investment and return. Risks of non-delivery arise from natural disturbances (e.g. pests, disease, biodiversity loss; Mori et al., 2021), climate extremes (e.g. wildfires, droughts, storms; Anderegg et al., 2020, 2022; Weiskopf et al., 2020), non-compliance (e.g. illegal logging, contract breaches; Fujii et al., 2024; Gifford, 2020), governance challenges (e.g. unclear property rights, enforcement gaps; Chan et al., 2023; MacKenzie et al., 2012), and regulatory uncertainty (zu Ermgassen et al., 2025). Several mechanisms are therefore in place to assess and manage financial as well as climate, environmental and social risks associated with investment in nature-based carbon removal projects. Conducting due diligence forms part of standard procedures to identify not only financial risks, but also other types of risks linked to project implementation. It serves to ensure that projects meet quality and integrity standards and align with sustainable development goals, with its findings informing the decision-making process regarding investment transactions. Moreover, staged investment structures are commonly applied, whereby funding is released incrementally upon the achievement of predefined project milestones. In addition, a range of instruments including certification and independent verification, guaranteed offsets, insurance, and hedging can be used to mitigate financial risks (Chan et al., 2023; Rau et al., 2024b; Tarnoczi, 2017). These mechanisms seek to reduce investment risk through risk transfer and risk distribution across different actors. The academic literature further proposes additional strategies for managing project risks, including robust baselining procedures (Swinfield et al., 2024; West et al., 2020), conservative estimation of project outcomes (Haya et al., 2023; Swinfield et al., 2024), and the optimization of credit release schedules to limit both the risk of credit reversal (Rau et al., 2024a) and the risk of project underperformance or failure to generate credits (Rau et al., 2024c).

2.3 Limitations of financial risk mitigation

While financial risk mitigation strategies aim to protect investors from losses due to credit non-delivery or reversal, they do not necessarily address the environmental and social harm that may result from project failure. This reflects the limited substitutability of different forms of capital, such as financial and natural capital: financial compensation may not restore ecosystems after irreversible damage. Moreover, financial insurance transfers risk across society rather than reducing it or minimizing material impacts through adaptation measures.

To address potential climate, environmental and social risks, most carbon credit programs and standards require project-level safeguards and risk mitigation measures. These include environmental and social safeguards and specific risk mitigation requirements in methodologies (e.g., Gold Standard, 2013). Environmental and social safeguards are policy instruments designed to prevent or minimize harm to people and the environment in project design and implementation, including in nature-based carbon projects.

The concept of environmental and social safeguards was originally developed by multilateral development banks, particularly the World Bank and the International Finance Corporation, which introduced Environmental and Social Safeguards Policies, later replaced by the Environmental and Social Framework and Performance Standards on Environmental and Social Sustainability. The UNFCCC and REDD+ subsequently applied the Cancun Safeguards, specifically targeting forest carbon projects. Social safeguards in particular promote the inclusion and participation of Indigenous Peoples and local communities in carbon project design and implementation (Bonfante et al., 2010).

This is supported by academic literature emphasizing that project success depends on social-ecological embeddedness, local participation, and community governance at the project level (Griffiths et al., 2020; Löfqvist et al., 2023; zu Ermgassen & Löfqvist, 2024). Furthermore, these safeguards align with equity and justice principles that require the participation and leadership of Indigenous Peoples and local communities to ensure positive local outcomes in terms of livelihoods, equity, and justice (Herr et al., 2019; McDermott et al., 2013).

2.4 Shortcomings in implementing safeguards and adaptation measures

However, academic literature continues to report shortcomings in the implementation of social safeguarding measures and in addressing climate risks in some carbon projects (Ashraf & Karaki, 2024; Haya et al., 2024). Moreover, environmental safeguards remain rarely discussed. Wissner and Schneider (2022) therefore recommend developing safeguards that specifically address risks to particular environmental components, such as biodiversity. This recommendation aligns with broader literature suggesting the integration of targeted activities, such as mechanical thinning in forestry to reduce wildfire risk, into adaptation and risk mitigation strategies at the project level (Daigneault et al., 2010; Herbert et al., 2022; Hurteau et al., 2008; McWethy et al., 2019).

In a similar line of argument, studies propose transitioning towards an adaptation and resilience management approach in forest-based carbon project development, to enhance system robustness and flexibility in dealing with unforeseeable challenges and to promote the long-term sustainability of projects (Wells et al., 2023). While financial mechanisms, such as insurance, can help manage financial risks and regulatory uncertainty, social-ecological resilience management can strengthen ecosystem resilience to multiple risks to project success, including those that are uncertain or not yet known, and which cannot be mitigated through financial instruments alone. Different risk mitigation measures are therefore applicable for managing, reducing, or adapting to different types of risks — financial, climate-related,

environmental, and social — and can be combined into integrated strategies that draw on both financial instruments, capacity- and nature-based measures for risk mitigation and adaptation on the project level.

3. Co-benefits and interconnected nature of ecosystems

3.1 Co-benefits and interconnections between ecosystem components

One potential pathway for enhancing the integration of adaptation and resilience measures into carbon projects is through their inclusion as project co-benefits. Carbon projects often aim to generate co-benefits such as enhanced local biodiversity, improved livelihoods, and contributions to equity and justice (Lam et al., 2024; Swinfield & Balmford, 2023). In the voluntary carbon market, co-benefits are typically not priced as separate value items but may increase the perceived value of the credit itself, enabling projects with strong co-benefits to command higher prices (Lou et al., 2022). In compliance or regulated carbon markets, co-benefits are not reflected in pricing, leaving ecological components beyond carbon storage and sequestration un- or undervalued.

By contrast, environmental sciences emphasize the interconnectedness of ecological components. Díaz et al. (2009) argue that biodiversity in carbon projects should not be treated as a disconnected "side benefit" but recognized for its stabilizing and productivity-enhancing role within forest ecosystems. Empirical studies demonstrate that both the carbon storage potential and overall productivity of forests increase with higher tree and plant species diversity (e.g., Liang et al., 2016; Liu et al., 2018; Mori et al., 2021; Weiskopf et al., 2024). Other studies highlight the stabilizing effect of tree species diversity on the forest carbon cycle and carbon storage over time (Qiao et al., 2023; Silva Pedro et al., 2015; Thurner et al., 2017; Zhang et al., 2024). Biodiversity hence stabilizes but also increases carbon sequestration and storage in forests. The knowledge used to manage nature-based climate solutions — whether in project design, carbon accounting, or financing — reflects differing domain perspectives and objectives, which shape how biodiversity, carbon, and other ecosystem components are valued and governed.

3.2 Challenges from differing domain knowledge representations

Domain knowledge of nature-based climate solutions is represented through varying perspectives and objectives across decision-making levels and disciplinary fields. The knowledge applied in managing land and forests for carbon credit delivery ultimately shapes how biodiversity, carbon, and other ecosystem components are governed and how their interconnections are addressed. Research shows that differing knowledge representations, and conflicts between them, influence land management by shaping carbon accounting, market design, financing mechanisms (Buongiorno et al., 2015; Díaz et al., 2018), policy and regulation (von Hedemann et al., 2021), project protocols (Badgley et al., 2022; Haya et al., 2020), or monitoring practices (Cole et al., 2024). Like model uncertainty in research, knowledge representations can create blind spots, limiting or distorting management options when ecological or social dimensions are overlooked (Goldstein et al., 2019). In these cases, addressing potential trade-offs or unintended effects from simplified or fragmented representations is crucial (Strange et al., 2024). Further, if acknowledged, differences in knowledge representation can also be used in productive ways (Clark et al., 2024). Strengthening environmental safeguards and leveraging ecological components for mitigation of environmental and climate risks, adaptation and resilience may become feasible by complementing carbon finance with more elaborate methods from natural capital accounting. These can account for some of the relations between ecosystem elements as demonstrated through scientific evidence and enable their integration on the level of accounting and financial decision-making.

4. A natural capital accounting approach: Biodiversity and ecosystem insurance value

A natural capital concept which satisfies conditions for integrating ecosystem components into natural capital accounting for environmental and climate risk mitigation, adaptation and resilience efforts specifically, is the concept of biodiversity or ecosystem insurance value. Biodiversity or ecosystem insurance assigns an economic value specifically to the risk-reducing capacities of natural capital such that they can be considered in financial decision making (Baumgärtner 2007; Dallimer et al., 2020; Hahn et al., 2021; Quaas et al., 2019; Pascual et al., 2010). Therefore, these concepts can be particularly useful to leverage ecological components for environmental and climate risk mitigation, adaptation and resilience, while enabling their consideration on the level of natural capital accounting. There exist many varying approaches in the academic literature to conceptualizing biodiversity or ecosystem insurance value for natural capital accounting. Although two broad directions have been distinguished, an economic conception and an ecological conception of insurance value, a closer look reveals additional nuances of directions.

4.1 Economic conceptions of biodiversity and ecosystem insurance value

In the economic conceptions of biodiversity or ecosystem insurance as developed by Baumgärtner (2007), Baumgärtner and Strunz (2009), Quaas et al. (2019), and others, insurance is modeled similar to an investment into financial insurance. The insurance value of biodiversity or natural capital is the value derived by a risk-averse ecosystem user or investor from a marginal increase in biodiversity or ecological components to reduce the variance of ecosystem output. It is based on the reduction of the risk premium which the user is willing to pay to avoid uncertainty of ecosystem service provision through an additional increase in natural capital. The insurance value of natural capital is assigned relative to its marginal utility, reflecting the additional benefit that each incremental increase in biodiversity or other natural capital components provides through risk mitigation and ecosystem stability. Biodiversity insurance is here conceptualized as inherently relational. It derives its insurance value from interconnected ecological components such as biodiversity and ecosystem output in the form of provision of goods or services. While there exist other ways in natural capital accounting to relate value components of ecosystems (Daily et al., 1997; Kumar, 2010), the insurance value links risk-reducing ecological components to ecosystem output (Baumgärtner, 2007; Baumgärtner and Strunz, 2009; Quaas et al., 2019) and is hence additional to the ecosystem's output value. Hahn and colleagues (2023) have suggested considering the expected mean outcome of ecosystem provision as a more adequate measure to assess biodiversity insurance than reducing variance. These manifold internally stabilizing relations between different ecosystem processes and components have long been recognized (Folke et al., 2021; Folke, 2006; Holling, 1973; Isbell et al., 2015). The concepts of biodiversity or ecosystem insurance and their value make use of these connections in the context of integrating and leveraging these for ecosystem management. Although biodiversity insurance is conceptualized as an ecosystem-internal risk-reducing mechanism, where relations between specific components of an ecosystem stabilize its provision of services and goods, this mechanism can contribute to the mitigation of ecosystem-external risks, such as securing the supply of food or clean water. Ecosystem insurance in the economic sense has been modeled for agroecology (Di Falco and Chavas, 2006), forestry (Hahn et al., 2021) and for non-timber products from forestry (Pattanayak and Sills, 2001).

4.2 Ecosystem-based adaptation (EbA) and disaster risk reduction (DRR)

Another economic conception of risk mitigation and adaptation through ecosystems exists in the literature on ecosystem-based adaptation (e.g. Brink et al., 2016; Donatti et al., 2020) and disaster risk reduction (e.g. Marchal, 2019; UNEP FI, 2023; UNDRR, 2020). Nature-based solutions are here evaluated and valued regarding their capacity to reduce physical risk exposure and vulnerability and reduce potential negative impact from climate- or nature-related risks and external hazards through their regulating ecosystem services (Narayan et al., 2017; Schwarze et al., 2011). Ecosystem-based risk mitigation and risk adaptation can be distinguished, where the first refers to lowering the propensity of the occurrence of a loss event, and the latter refers to mitigation of the extent of the loss itself. Typically, nature-based solutions for disaster risk reduction are discussed as an ecosystem-based adaptation measure to reduce the vulnerability and exposure to a risk and reduce the potential damage of or loss from an event. Value is derived from the use of regulating ecosystem services such as water and climate regulation, natural hazard protection, disease and pest regulation. It can be assigned based on the damage costs that the provision of an ecosystem service such as flood mitigation helps avoid and can be considered a part of an ecosystem's use value (Kumar, 2010). However, Dallimer et al. (2020) discuss multiple further valuation metrics such as benefits or price, and methods of valuation for different ecosystem-based risk mitigation and adaptation measures as found in empirical studies indicating a lack of standardization in valuing nature's contributions to risk mitigation and adaptation. In contrast to the biodiversity insurance value modeled on financial insurance, which refers to ecosystem-internal risk reduction, the approach to risk mitigation and adaptation through nature-based solutions often discusses their buffering effect against ecosystem-external disturbances such as floods, storms or other extreme climate events.

4.3 Real options and portfolio theory for valuing an ecosystem's resilience stock

Two additional natural capital valuation approaches can be taken into account, especially when it comes to considering the long-term stability of ecosystems and sustainable management that is required to maintain their ability to recover from, absorb and adapt to disturbances. Both relate to valuing natural capital under changing conditions and over time to ensure sustainable and stable ecosystem maintenance. One is the real options and quasi-options approach which highlights, for instance, how species substitutability can add value rather than diminish it (e.g. Kassar and Lasserre, 2004; Pascual et al., 2010). Species act as assets that an ecosystem manager or society preserves for their potential to provide essential goods or services under changing conditions. The value derived from biodiversity lies in the option to substitute one species with another, which underlines the importance of preserving species that seem redundant. A related framework which specifically seeks to assign value to different ecological components as diverse assets of an ecosystem is the application of portfolio theory to ecosystems and biodiversity (e.g. Admiraal et al., 2013). This approach helps value biodiversity beyond its direct economic benefits as a stabilizing component for maintenance of ecosystem stability and service provision. Both approaches - options and portfolio theory - can help value the underlying "resilience stock" of an ecosystem consisting of functional diversity and apparently redundant species as well as spatial links through mobile species or spatial and ecological connectivity. The resilience stock ensures the continued preservation of absorptive and adaptive capacities and the ability of an ecosystem to recover from disturbances and extreme events which are necessary prerequisites for an ecosystem's resilient functioning.

4.4 Ecosystem management for adaptation and resilience

In addition, ecosystem management practices contribute to either stabilizing or diminishing its capacities to maintain functioning in the face of disturbances and under changing conditions as well as to recover from disturbances. Academic literature argues for including ecosystem management practices explicitly for risk mitigation and adaptation management (see e.g. Herbert et al., 2022; McWethy et al., 2019 related to forest ecosystems and carbon management). Valuing different dimensions of resilience of or through an ecosystem requires consideration of the stewardship practices that facilitate its resilient functioning.

4.5 Ecological insurance concept

In contrast to the economic valuation of ecosystem-based risk reduction, the ecological conceptualization of ecosystem insurance (e.g. Loreau et al., 2021;Yachi and Loreau, 1999) studies the many relations between different ecosystem components and their moderating, enhancing or stabilizing effects on one another, without assigning a monetary value to these processes or outcomes. Therefore, the ways in which a certain ecosystem component, such as a specific biodiversity, stabilizes the provision of an ecosystem service, is often conceptualized in a multi-dimensional way rather than only by one measure of risk reduction such as reducing the variance of ecosystem output. However, the study of ecological relations is a prerequisite for applying natural capital concepts and valuation to ecosystems.

4.6 Integration of approaches into resilience value as a natural capital accounting framework

In the academic literature, the conceptualization of the insurance value of biodiversity or ecosystems varies not only regarding the ecosystem services and components it values, but also regarding the set and types of risks that it is meant to address and how it is meant to mitigate or help adapt to risk. Further, the way risk is conceptualized in the different approaches differs (*Table 1*). A concept which can potentially integrate these different approaches is the full resilience value of an ecosystem as recently suggested by Hahn et al. (2023). The resilience value is assumed to go beyond valuing specific risk-reducing functions and establish a general resilience value of an ecosystem in the face of multiple disturbances and for multiple stakeholders over time. The authors also suggest addressing the increasing ecosystem vulnerabilities which happen through slow erosion of the resilience stock such that the possibility arises that an ecosystem reaches a threshold and switches states or regimes. Another valuation perspective emerges from this comparison of the resilient functioning of an ecosystem across different states or regimes (Pascual et al., 2010; Walker et al., 2009a, 2009b, Walker and Meyers, 2004). An ecosystem's resilience value could serve as a context-sensitive framework in natural capital accounting that aggregates several value components that a social-ecological system contains specifically for resilience and adaptation relative to its current state, relative to specific hazards, its risk exposure and vulnerability. This could complement the IPCC conceptualization and guidance on climate-related risk as the product of hazard, exposure, and vulnerability (Reisinger et al., 2020).

In conclusion, rather than subsuming the different approaches under the umbrella term "insurance value", they can be categorized by their value assignment to various risk mitigation and adaptation capacities of natural capital. The overview in *Figure 1* broadly distinguishes ecological and natural capital approaches contributing to an ecosystem's overall resilience value. These can be seen as mutually supportive and complementary.

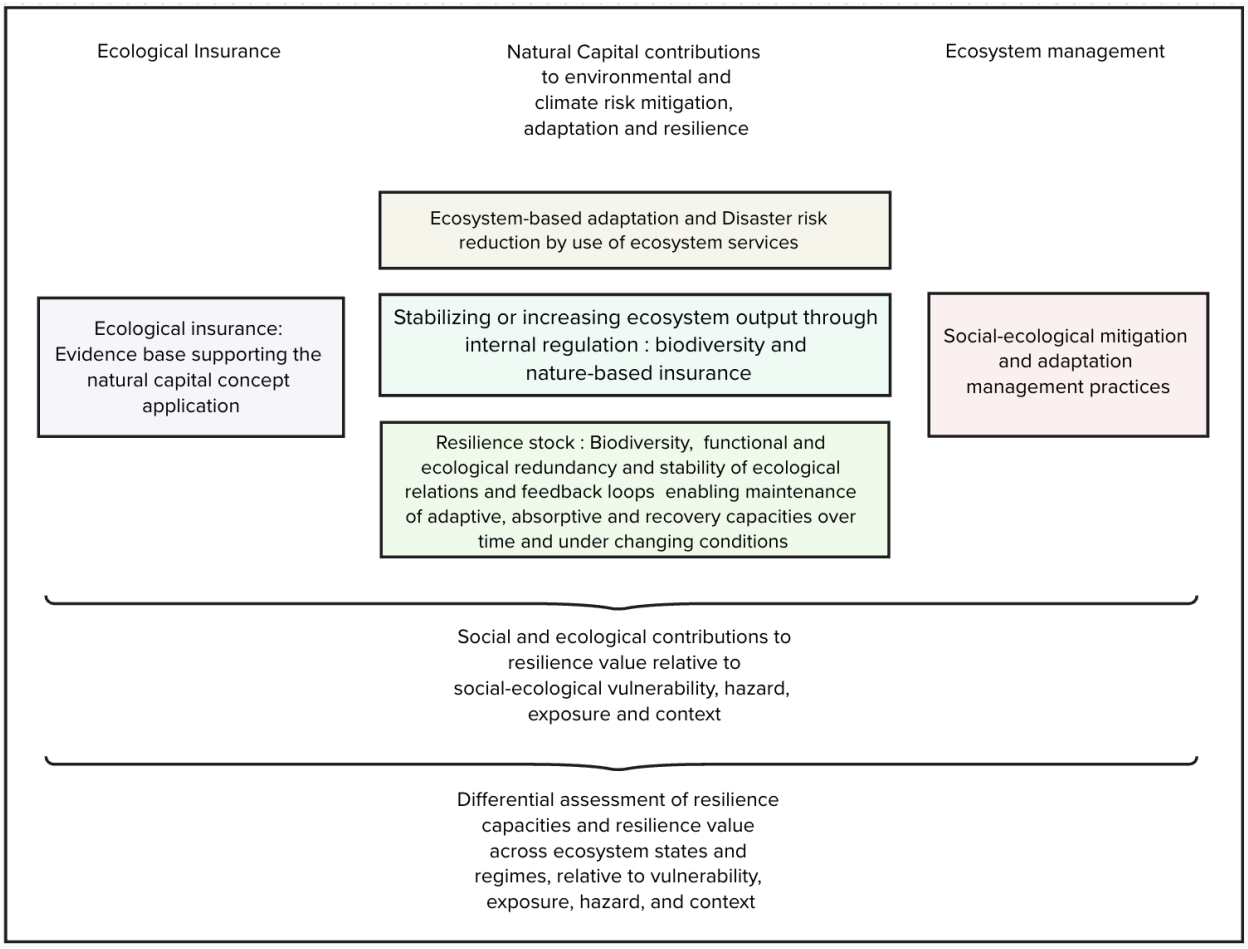


Figure 1: Broad overview of nature-based insurance perspectives contributing to the resilience value of ecosystems.

Ecological insurance: Environmental studies of ecological insurance effects provide the evidence base for natural capital accounting approaches that make use of these mechanisms when valuing biodiversity or natural capital in their specific risk mitigation or adaptation capacity.

The economic approaches to nature-based risk mitigation and adaptation refer to different fractions or processes of natural capital:

Biodiversity and natural capital's insurance value refers to the internal risk-reduction capacity of ecosystems, safeguarding the provision of ecosystem goods and services. This can be valued, for instance, through the reduction of variance in service provision (Baumgärtner, 2007), or through the increase in mean service levels associated with higher biodiversity (Hahn et al., 2023).

Ecosystem-based adaptation (EbA) (e.g. Brink et al., 2016; Nalau et al., 2018) **and disaster risk reduction (DRR)** approaches (e.g. Marchal et al., 2019; Narayan et al., 2017; Schwarze et al., 2011) typically focus on the external protective functions of ecosystems, their ability to regulate and buffer against natural hazards, extreme climate events, and other disturbances. These approaches assess value, e.g. based on the reduction in potential damages or losses due to ecosystem-mediated regulation.

The option value of biodiversity, often framed through portfolio theory, captures how biodiversity underpins both internal and external risk-mitigating mechanisms, while emphasizing the importance of maintaining these capacities over time (Admiraal et al., 2013; Kassar and Lasserre, 2004). This includes

the resilience stock of ecosystems, their absorptive and adaptive capacities, as well as their ability to recover from disturbances.

Targeted ecosystem management practices can reduce specific risks and enhance adaptive or absorptive capacity, and capacity for recovery, contributing to an ecosystem's overall resilience value.

Comparing resilience and adaptation capacities across ecosystem states or regimes offers yet another perspective for valuation. Resilience value should be assessed relative to an ecosystem's current risk exposure and vulnerability profile, recognizing that different systems may require different strategies and indicators depending on their stressors and adaptive potential.

5 Application of nature-based insurance to carbon project development

Many different conceptions of nature-based insurance values can in theory be applied to a carbon project from forestry. In practice, such an effort poses challenges in operationalization of the natural capital concepts as well as for data acquisition, modeling and analysis required to assess the specific risk mitigation potential of ecosystems and management practices relative to the hazard, risk exposure and ecosystem vulnerability. However, following the conclusion from the previous section that economic concepts of nature-based risk mitigation require evidence of ecological insurance effects in order to be applicable, Baumgärtner's model (2007) is particularly well suited for capturing the stabilizing function of tree species diversity for carbon storage and sequestration (Qiao et al., 2023; Silva Pedro et al., 2015; Thurner et al., 2017; Zhang et al., 2024). Baumgärtner's description focuses on the role of biodiversity as insurance for reducing variance of a specific ecosystem service output, in this case, carbon sequestration and storage. Additionally, the case of carbon credits from forestry aligns with further application conditions for his model (Baumgärtner, 2007, p.110):

1. Ecosystem users and investors are risk-averse.
2. Financial insurance for carbon projects is available.
3. The level of biodiversity impacts the probability distribution of the ecosystem service and, thus, of income from carbon credits, and
4. The insured and carbon insurer have the same *ex ante* knowledge about the distribution of carbon sequestration provision.

The exact insurance effect of biodiversity within a forest ecosystem has to be specified relative to the particular geography, type, use, age, management objectives and disturbance history, composition and structure of the forest ecosystem and its specific social-environmental conditions. Specific metrics such as tree α-diversity, species richness, abundance and statistical methods have to be adjusted accordingly. Further, if biodiversity as an insurance is specifically valued in its role to secure carbon sequestration, safeguarding measures are required to ensure that this does not lead to tradeoffs in forest management to prioritize stewardship for the stability of the carbon cycle at the expense of other biodiversity outcomes. Studies exist which outline forest ecosystem conditions in favor of both objectives, carbon storage and biodiversity, relative to a specific geographic context which can be supportive for natural capital concepts (Springer et al., 2024).

In the remaining sections, Baumgärtner's model of biodiversity insurance and its potential application to the carbon project case is discussed. This is followed by a brief description of how a full resilience value as outlined by Hahn et al. (2023) goes beyond the internal mitigation concept of ecosystem insurance. The concluding section provides an outlook on the necessities for improved modeling and operationalization of nature-based insurance approaches to enable their practical applicability.

5.1 Biodiversity-carbon relationship as insurance value in carbon forest management

Baumgärtner (2007) conceptualizes the insurance value of biodiversity as the benefit derived by a risk-averse ecosystem manager from reducing the risk premium R associated with the manager's uncertain income from ecosystem service provision by marginally increasing biodiversity. In Baumgärtner's model, the manager derives their income y from ecosystem service provision s such as carbon sequestration. This ecosystem output is modeled as a normally distributed random variable with mean μs and standard deviation σs and so is the manager's associated income. It is assumed that the mean level of ecosystem service provision increases and its standard deviation decreases in proportion to the level of biodiversity v in the ecosystem. Investing in the level of biodiversity v reduces the variance of ecosystem service outcome s. As mentioned, the relation of biodiversity and carbon within a specific forest ecosystem has multiple dimensions and can be further specified. To facilitate applicability, it is here assumed that tree species diversity increases and stabilizes carbon storage and sequestration in a forest ecosystem. The distribution of the ecosystem service s is conditional on the level of biodiversity v in the ecosystem. Investing in biodiversity comes at a cost C for the manager. Then, the net income y of the ecosystem manager when using biodiversity as a natural insurance is the benefits B they derive from the ecosystem service output s minus the costs C of their investment into biodiversity v:

$$y = B(s) - C(v) = s - C(v).$$

Writing $B(s) - C(v) = s - C(v)$ is a simplification indicating that the monetary benefit B is directly proportional to the quantity of s.

5.2 Risk aversion and conditional variability

Baumgärtner's concept of biodiversity insurance value V depends on (1) the dependence of the variability of the ecosystem service s, here carbon sequestration, on the level of biodiversity v and (2) the degree of risk aversion of the ecosystem manager. Investors and project developers in carbon finance can be assumed to be risk averse which is why financial insurance for carbon projects exists. Baumgärtner captures these assumptions in his Proposition 1:

$$V(v) = -\rho \sigma s(v)\, \sigma s'(v) > 0.$$

where ρ is the ecosystems manager's degree of risk aversion, $\sigma s(v)$ is the standard deviation of ecosystem service output s at a level of biodiversity v and $\sigma s'(v)$ the derivative of the standard deviation which indicates the rate of change of the standard deviation σs with respect to changes in biodiversity at level v. The insurance value V of biodiversity v increases with the degree of the ecosystem manager's risk aversion and with the degree of sensitivity of the standard deviation of ecosystem service provision s on changes in biodiversity v. If this sensitivity measure is high, the power of biodiversity to regulate uncertainty of ecosystem service provision increases, and hence its insurance value increases.

5.3 Uncertainty definition

The uncertainty of an ecosystem output is modeled by Baumgärtner as an infinite set of lotteries. The risk premium R represents the amount a decision maker is willing to pay to avoid the uncertainty of a particular lottery. The higher the risk aversion of the manager, the higher the amount they are willing to pay to avoid risky outcomes. In Baumgärtner's approach, the risk premium R of the lottery depends on the level of biodiversity v in an ecosystem. More specifically, given the conditionality of ecosystem service provision s on the level of biodiversity v, when choosing a particular level of biodiversity, the ecosystem

manager determines a distribution of an ecosystem service, carbon sequestration, which then determines the distribution of their income from carbon credits based on the ecosystem's carbon uptake.
The insurance value V of biodiversity v is then defined by Baumgärtner as the change of the risk premium R due to a marginal change in the level of biodiversity v:

$$V(v) := -R'(v).$$

By changing the biodiversity level, the manager can potentially reduce uncertainty and hence reduce the amount of R. The insurance value derives from the reduction in R that an investment into biodiversity provides. Applied to the case of land and forest management activities for carbon, this implies that, depending on the level of existing tree diversity, risk aversion and management options, investors or ecosystem managers may face the decision of investing more in biodiversity to reduce the variance of carbon outcomes.

5.4 Optimization with and without financial insurance

In Baumgärtner's model, the ecosystem manager seeks to maximize his expected utility by choosing an optimal level of biodiversity. Further, they seek to allocate resources efficiently considering the benefits and costs associated with biodiversity. Baumgärtner first examines how a risk-averse ecosystem manager makes use of the biodiversity insurance function if no financial insurance is available. In this situation, the manager keeps investing in biodiversity to the point where the marginal benefit from an increase in biodiversity in terms of ecosystem service provision and biodiversity insurance value equals the marginal cost of biodiversity maintenance or enhancement. This characterizes the optimal level beyond which any additional investment yields zero or a diminishing gain. Baumgärtner's approach hence incorporates three factors that influence investment behavior: risk aversion, efficient resource allocation and utility maximization. Risk aversion drives investments to reduce uncertainty, while utility maximization and efficiency in allocation ensure that investments in biodiversity continue until the marginal benefits derived from the stabilization and enhancement of ecosystem services such as carbon sequestration, equal the marginal costs of investment. Relating this to the case of income from carbon credits, the risk premium can be more accurately conceptualized as reflecting the manager's aversion to uncertainty and the potential loss in market value dependent on the carbon price due to variability in outcomes. Where the manager's or investor's income is dependent on the market price of carbon, this is a further external factor influencing their investment decisions.
When financial insurance is an option, the ecosystem manager or investor decides on both the level of biodiversity and the extent of financial insurance coverage to maximize their expected utility. In Baumgärtner's approach, financial and biodiversity insurance act as substitutes and can both help reduce the overall risk or variability of returns from natural resources. The ecosystem manager's net income is then defined by several factors: the provision of ecosystem services, the costs and benefits from biodiversity insurance, and the expenses for financial insurance coverage. The manager allocates resources optimally between investing in biodiversity insurance and in financial insurance, while the investment into financial insurance is dependent on its real costs. Baumgärtner concludes that a risk-averse ecosystem manager will always opt for a lower level of biodiversity when financial insurance is available, compared to a scenario without financial insurance. This might be due to the perceived higher reliability and better quantification of risk in financial insurance. It suggests, however, that without additional incentives or regulations, investors may overlook the ecological benefits and benefits of environmental and climate risk reduction of biodiversity in favor of financial instruments that spread risk rather than reduce it. This stresses the importance of policies that promote or incentivize biodiversity

investment. In the case of nature-based carbon projects, this implies that the access to financial carbon insurance could disincentivize an investment into biodiversity as a nature-based insurance mechanism if the insurance does not consider risk mitigation measures using natural resources or if there is no policy in place that incentivizes investment into natural capital as an insurance mechanism. Similar cases have been discussed in financial insurance of natural resources, e.g. in farming, where financially insuring crops might disincentivize sustainable farming. This suggests that nature-based insurance should be considered and valued when financially insuring natural resources and their management. The assumption of substitutability of financial and nature-based insurance in Baumgärtner's model serves to highlight the potential tradeoffs when both options are available but is questionable in reality, not only regarding long-term effects of these investment choices.

5.5 Optimizing for stability or for system performance?

While Baumgärtner's model emphasizes the insurance value of biodiversity as its ability to reduce variance in ecosystem service provision, other scholars such as Hahn and colleagues (2023) argue that maximizing expected outcomes should be the main objective of ecosystem management. In Baumgärtner's framing, biodiversity stabilizes ecosystem outputs under uncertainty, offering value to risk-averse decision-makers by reducing the risk premium and enhancing predictability. Hahn, by contrast, contends that biodiversity should not only mitigate risk but also enhance average system performance, such as increasing the mean rate of carbon sequestration. Empirical evidence in the environmental sciences suggests that biodiversity does both: it reduces variability and increases mean levels of ecosystem services (Isbell et al., 2017). This dual function strengthens the case for biodiversity as a substantial component of climate and land-use strategies, supporting risk reduction and outcome optimization in policy and investment decisions. The distinction also reflects a broader debate in ecological economics about whether biodiversity's primary value lies in risk mitigation or in improving average performance and how these values should be reflected in management objectives. Particularly in carbon forestry, research has shown that biodiversity both stabilizes the forest carbon cycle (Qiao et al., 2023; Silva Pedro et al., 2015; Thurner et al., 2017; Zhang et al., 2024) and increases total carbon outcomes (e.g., Liang et al., 2016; Liu et al., 2018; Mori et al., 2021; Weiskopf et al., 2024). These findings reinforce the importance of maintaining or enhancing biodiversity not just for ecological resilience but as a strategic priority for carbon-focused land management and climate finance.

5.6 Including biodiversity insurance in carbon project finance

A question is how and where biodiversity insurance mechanisms can be integrated into carbon project finance. One option is to include a biodiversity insurance value component as a co-benefit of project outcomes, without replacing standalone biodiversity co-benefits. Alternatively, nature-based carbon projects could be complemented with biodiversity (insurance) credits. Further, environmental safeguards could be specified according to ecological insurance mechanisms and their implementation disclosed in financial reporting about projects and ecosystem maintenance. Biodiversity insurance could also be integrated in requirements for financial insurance for carbon projects (UNEP FI, 2024). The discussion around integration of the biodiversity-carbon relationship into climate finance highlights potential avenues for innovation to adapt nature finance instruments and their performance metrics to ecological dynamics. Since biodiversity not only reduces downside risk of project underperformance but also increases expected returns, including biodiversity in carbon finance could be expressed in metrics of risk-adjusted returns. Given that reducing downside deviation rather than total volatility of carbon outcomes is more relevant in the context of carbon finance, a higher Sortino ratio could express better

performance of a biodiversity-insured carbon investment. In contrast, the Sharpe ratio could help assess risk-adjusted returns considering total volatility.
Following Baumgärtner's model, the description here specifically relates carbon sequestration and tree species diversity as the latter providing insurance for the former which can be operationalized and applied in more detail to a real carbon project from forestry. An increase in biodiversity in a forest potentially not only enhances and stabilizes carbon sequestration or storage but also other ecosystem functions and services. It further can reduce or mitigate other risks than those of variance in carbon output. However, if the aim is to provide broader carbon project resilience in the face of different types of climate-related, nature-related and social risks, implementation of further ecosystem management options is required.

5.7 Resilience value: **accounting for objective risks**

To account for broader resilience of an ecosystem and its resilience value in the face of climate change, Hahn et al. (2023) argue that these climate- and nature-related risks are what they call objective risks - risks that are not contingent on subjective risk preferences. Consequently, in the face of such objective risks, the insurance value of ecosystems is its "full resilience value": it also addresses the objective risks of climate change, nature-related risks and social risks. Objective risks may be conceptualized as risks that exist independently of their perception as risks from certain agents, whereas subjective risks exist dependent on the specific conditions and choices of a certain risk-taking perspective. An agent may choose to ignore or deny the existence of risks associated with climate change; however, these risks can still materialize when their assets are affected by a climate-change-induced event. While the recognition of such risks is a matter of perception or choice, exposure to their consequences is not. Nevertheless, agents often have the option to mitigate or reduce these risks through targeted management interventions, including the use of ecosystems and nature-based solutions. In contrast, when facing subjective risks, such as those involved in investment decisions, an agent retains full discretion over whether to assume a given risk or avoid it altogether.
A further way of understanding the distinction between objective and subjective risks is dependent on whether the risk perspective only considers private costs and benefits or also social costs and benefits. Another distinction can be drawn relative to the public good nature of ecosystems and its implication of being non-excludable. Nature-based risk reducing services of ecosystems such as drought or flood mitigation are non-excludable, too, and do not only address subjective risk preferences. They are more inclusive by nature, mitigating risks of different types for all stakeholders, because they are a part of how ecosystems function. Hahn et al. (2023) argue for assessing the full resilience value of ecosystems which aims to be more comprehensive than single nature-based risk reduction measures. To meet the requirements of mitigating internal and external risks, and objective instead of only subjective risks, the resilience value of nature-based insurance needs to take into account several risk-reducing services and components relative to multiple risks, independent of a specific user perspective. There exist challenges regarding the operationalization and applicability of a resilience value, but efforts to do so could build on the various natural capital approaches to valuing nature-based environmental and climate risk mitigation and adaptation that are already available: the valuation of nature-based solutions in ecosystem-based adaptation and disaster risk reduction, the ecosystem-internal insurance mechanisms, as well as the portfolio and the options approach to valuing the maintenance of a "resilience stock" over time and under changing conditions and targeted ecosystem management interventions.

5.8 Challenges in operationalization of resilience value

The inclusion of nature- and climate-related risks into conceptions of nature-based insurance additionally necessitates a change in their statistical operationalization. More specifically, resilience through buffer or insurance effects can stabilize ecosystem services provision not only relative to normally distributed ecosystem services, such as in the model described by Baumgärtner (2007), but also relative to their distributions under and after extreme climate and nature-related events and potential regime shifts. The operationalization of resilience value of an ecosystem undergoing extreme events not only requires a dynamic and variable conceptualization as e.g. in Quaas et al. (2019) but also an improved understanding of how risks are compounded by environmental factors or systemic vulnerabilities. It requires understanding the ecosystem responses to climate events (Anderson-Texeira et al., 2022) and the interactions of ecosystems with climatic conditions such as the coupling of the carbon and water cycle (Gentine et al., 2019).

6 Conclusion

Climate adaptation, resilience management and finance is already an important topic in risk assessments, mitigation and adaptation efforts in the financial, public and corporate domain (Baer et al., 2023; Mullan, 2024; Mullan and Ranger, 2022; World Bank, 2024). Research indicates that nature-based carbon projects require specification of social and environmental safeguards to integrate natural capacities and management activities for physical risk mitigation of climate change and nature-related risks (Wissner & Schneider, 2022). Although the concept of environmental and social safeguards is in use, there are shortcomings in its implementation (Haya et al. 2024). Addressing risks in their double or planetary materiality (Crona et al., 2023; Wassénius et al., 2024) requires integrating different means into comprehensive risk mitigation strategies. Those strategies can leverage and incorporate natural insurance through nature-based mitigation and adaptation. Increasing resilience value within a carbon forest project implies implementation of adaptation and resilience measures that not only mitigate risks of uncertain ecosystem service provision, such as by enhancing tree species diversity, but also include strengthening the overall resilience of ecosystems in the face of disturbances. A customized approach to natural capital valuation for resilience specifically in carbon forest management could integrate resilience and adaptation practices across potential disturbances and management objectives that are considered relevant relative to a specific project context, its vulnerability and the risk exposure of that project. Environmental mitigation and adaptation measures can then be complemented by social resilience considerations supporting local communities and the sustainability of their livelihoods. Existing frameworks such as the World Bank Resilience Rating system (2021) can further help design and evaluate project-specific strategies to increase carbon project resilience in the face of climate change.

The concepts of biodiversity insurance and ecosystem resilience value (Baumgärtner, 2007; Hahn et al., 2023; Primmer and Paavola, 2021; Quaas et al., 2019) provide valuable starting points to integrate environmental components into natural capital accounting for insurance pricing or valuing nature-based risk mitigation and adaptation. The economic approach to ecosystem-internal natural capital insurance to mitigate uncertainties of specific ecosystem service provision can be valuable in investment decision-making contexts as well as to integrate nature insurance value into financial insurances because it is modeled similar to a financial insurance mechanism. The economic approach modeled on nature-based solutions, in turn, additionally incorporates external risk-regulation and resilience stock when valuing nature-based solutions. A full resilience value could further specify how different natural capital components for risk mitigation and adaptation integrate and combine. It highlights the necessity to

distinguish different types of risks and the varying requirements for their reduction and mitigation, but is in need of methodological improvement regarding its operationalization and potential applicability.

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Table 1: Nature-based insurance concepts, their risk focus and example metrics and references

Insurance Concept	**Risk Focus Areas**	**Example Metrics**	**Example References for Concept and/or Valuation**
Ecological Insurance: Ecosystems have various risk mitigation and adaptation capacities and buffering capacity against internal and external variance and disturbances.	• Loss of critical ecological functions (e.g., pollination, water retention) • Threshold events in ecosystems (e.g., bleaching, dieback, trophic collapse) • Functional degradation under stress • Cascading ecological failure • Risk of delayed or insufficient restoration	• Ecological Trigger Thresholds • Service Loss Risk • Cascade Sensitivity • Ecological Recovery Time • Functional Resilience • Restoration Cost Estimate	• Loreau et al., 2021 • Yachi and Loreau, 1999
Biodiversity Insurance: Diversity reduces volatility/downside risk in ecosystem service delivery within an ecosystem.	• Downside volatility in ecosystem service delivery and/or variance of delivery • Functional instability due to low species richness • Long-term loss of adaptive capacity • Amplified risk under environmental fluctuations • Service loss due to degradation or disturbance	• Lower Partial Moments (LPM) • Downside risk metrics • Variance in Service Provision • Mean Expected Outcome • Conditional Value-at-Risk (CVaR) • Co-benefit Metrics • Functional Redundancy	• Baumgärtner, 2007 • Baumgärtner and Strunz, 2009 • Quaas et al., 2019

Nature-Based Insurance: Ecosystems reduce disturbance impacts and provide internal stability.	• Various conceptions • Asset damage from natural hazards (e.g., storms, floods, fires) • Service loss due to degradation or disturbance • Cost of ecological restoration or compensation • Spatial exposure of natural assets to hazard zones • Vulnerability	• Exposure and Vulnerability • Hazard Attenuation Metrics • Expected Restoration Cost • Protection Value • Residual Risk After Intervention • Return Period • Co-benefit Metrics	• Hahn et al., 2021 • Dallimer et al., 2020 • Di Falco and Chavas, 2006 • Pattanayak and Sills, 2001 • Pascual et al., 2010
Ecosystem-based Adaptation: Nature-based adaptation to climate risk.	• Climate-induced vulnerability • Risk to livelihoods and infrastructure • Maladaptation or misuse under stress • Loss of protective ecological functions • Inadequate capacity to respond to change • Delayed recovery after climate shocks	• Expected Damage Avoided • Hazard Exposure Reduction • Adaptive Capacity Index • Downtime / Recovery Time • Climate Risk Buffering • Risk Reduction Efficiency • Co-benefit Risk Correlation • Maladaptation Risk Score	• Brink et al., 2016 • Donatti et al., 2020 • Nalau et al., 2018 • PEDRR & FEBA, 2022 • UNEP FI, 2023, 2024
Disaster Risk Reduction: Minimizing hazard impacts, often through ecosystem protection.	• Acute natural hazards (e.g., floods, landslides, coastal storms) • Physical exposure of people and assets • Infrastructure disruption from environmental events • Loss and damage • Compounding risks (e.g., drought and fire, flood and contamination) • Service collapse during emergencies	• Hazard Probability and Hazard Reduction Metrics • Exposure & Vulnerability Reduction Metrics • Impact and Loss Reduction Metrics • Loss and damage accounting • System Function and Recovery Metrics	• Marchal et al., 2019 • Narayan et al., 2017 • Schwarze et al., 2011 • UNDRR, 2020 • UNEP FI, 2023, 2024
Resilience Stock: Ecosystem capacities to absorb, adapt to and recover from	• Erosion of systemic buffering capacity • Loss of structural and functional	• Functional Diversity • Ecological or Functional Redundancy	• Admiraal et al., 2013 • Kassar and

disturbances and for resilient functioning over time and under changing conditions.	ecosystem diversity • Inability to recover from acute, sequential or chronic stress • Decoupling of feedback mechanisms (e.g., soil loss, deforestation) • Latent risks accumulating in degraded systems	• Connectivity • Latent Capacity Utilization • Ecosystem Health • Social-Ecological Feedback Strength • Diversity-weighted variance or mean-variance trade-off • Portfolio Effect • Value of options	Lasserre, 2004 • Pascual et al., 2010
Resilience Value: Benefit of reduced risk, absorptive and adaptive capacities, and recovery due to resilience.	• Loss potential under extreme or uncertain future scenarios • Performance volatility in coupled human-nature systems • Cost escalation from delayed recovery • Weak return-to-baseline capacity • Reduced ability to adapt to novel conditions • Multi-risk exposure and vulnerability, multiple hazards	• Composite Metrics (sensitivity, adaptive and absorptive capacity) • System robustness (thresholds or tipping points) • Value-at-Risk • Ecosystem Vulnerability and Exposure • Critical Threshold Risk • Adaptive Capacity Score • Buffering Capacity • Probability of System Failure or Collapse • Recovery time after disturbance	• Hahn et al., 2023 • Pascual et al., 2010 • Walker et al., 2009a, 2009b • Walker and Meyers, 2004

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