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Discussion

Utilising portfolio theory in environmental research – New perspectives and considerations

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ABSTRACT

Modern Portfolio Theory is a well-established method in economic research for considering the risks and returns in asset allocations and the potential benefits of diversification for risk averse agents. Thus, it is a useful tool for guiding sustainability discourse under uncertain future states. Existing discussions around the method's use in environmental research have evolved during over the 75 years of its application, leading to a continued renewal of perspectives on utilising it. We classify the environmental questions where portfolio theory has been applied, and critically discuss the methodological approaches taken; providing a stepping stone for future use of the method. This article provides a framework for its application in environmental research using the following questions: 1) what is the type of research or management question and objective(s) of the decision-maker(s); 2) what are the definitions of the assets to be included in the portfolio; 3) what are the ways that returns are valued, discounted, distributed and weighted; 4) what is the most appropriate way for risks to be accounted for and managed, including the selection of the appropriate model and taking into account risk preferences; and 5) what are the definitions of constraints in the programming problem.

1. Introduction

The demand for practical, interdisciplinary and well-tested decision-making methods, in the context of environmental asset management decisions across temporal and spatial scales, is increasing (Guerry et al., 2015). Integrated tools must address the interlinkages between competing objectives over spatial and temporal scales (e.g. between forestry and agriculture, see Ferretti-Gallon and Busch, 2014) and the urgent need to concurrently mitigate and adapt to global change challenges (e.g. biodiversity loss, see Pimm et al., 2014; and climate change, see Duguma et al., 2014). Complex questions of sustainability related to new forms of risk and landscape-level trade-offs require research to assess and improve tools for providing guidance to users and decision-makers. In the context of these developments, one method, Modern Portfolio Theory (MPT), continues to receive attention from economic and environmental management researchers (see Figge, 2004; Ando and Shah, 2016; Alvarez et al., 2017). The evolving discussion around the utilisation of MPT in environmental research raises challenging questions; to which this article tries to respond.

MPT is a method for choosing an efficient portfolio of assets via mean and variance of (financial) return, as well as individual risk preferences (Elton and Gruber, 1997). It was first presented by Markowitz (1952, 1959) as a means for a decision-maker (e.g. an investor) to evaluate assets on the basis of the return relationship between different assets and their deviation (i.e. the covariance of expected returns) rather than an asset's individual characteristics alone. A brief description is presented in Appendix A. Although MPT still forms the backbone of financial theory, it has also been proposed as both a normative (i.e. as a recommendation for portfolio selection to reduce their exposure to the unsystematic risk of a single asset) and a positive (i.e. as a hypothesis about investor behaviour) method and tool for environmental management decisions (e.g. Castro et al., 2015).

For environmental management questions, portfolios often consist of alternative allocations, uses or groups of land (e.g. agriculture or

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conservation) or land-use management decisions (e.g. crop selection). This practice refers to von Thünen's theory (1826),[1] which has since been combined with the theory of portfolio selection (e.g. Macmillan, 1992).

Shortly after Markowitz (1952) first introduced the theory, researchers started applying MPT empirically to questions concerning human management of the environment. Heady (1952) noted that the land-use decision-maker is faced with the trade-off between long-run profits (returns) and short-run price risks (variance) - the goal being to utilize diversification to effectively reduce the variance of financial returns. McFarquhar (1962) applied MPT empirically to agricultural land-use planning, he used variance in income (as a function of yield) as a proxy for differing environmental impacts (e.g. climatic variance), to determine the optimal crop portfolio in the UK. Thereafter, MPT quickly became a popular method, used solely or in conjunction with other models, to determine efficient and optimal risky portfolios both for guiding environmental management interventions and to address the overutilization of and the resulting changes to ecosystems from management decisions. The application of MPT to current social welfare questions, such as those dealing with landscape level planning or to address global change trade-offs, are a product of those early investigations and even more timely in the context of global change dynamics (e.g. Schindler et al., 2010; Marinoni et al., 2011; Ando and Mallory, 2012; Sandsmark and Vennemo (2007)).

Several reviews and discussions have already been written on MPT's use, its challenges and limitations, by various authors (e.g. Figge, 2004; Ando and Shah, 2016; Alvarez et al., 2017) on its application to environmental questions. In addition to answering many important questions, those studies form an integral part of the long tradition of discourse around the method within natural sciences and economics (e.g. Robinson and Brake, 1979; Kruschwitz, 2005; Hyytiäinen and Penttinen, 2008). Recently, Alvarez et al. (2017) proposed a framework for applying MPT in the context of ecosystem service research or management questions. They created a list of four essential questions to rationalize the application of MPT to questions concerning ecosystem services: (1) the nature and objectives of the portfolio manager, (2) the definition of assets to be included in the portfolio, (3) the way in which returns and risk are measured and distributed, and (4) the definition of constraints in the programming problem. However, many important questions related to the use of the method were left unanswered by earlier reviews and discussions, for example those relating to new forms of return and risk and landscape-level trade-offs, and Alvarez et al.‘s four questions omit many of the key aspects of environmental management challenges (e.g. landscape level planning and multiple decision-makers).

In response to both the earlier reviews and discussions, and Alvarez et al.‘s framework, we believe that the applicability of MPT merits further study and a framework that more broadly accounts for the use of this method across environmental research applications. For example, a framework that considers different types of decision-making levels or contexts (e.g. market and non-market benefits from ecosystems for one or more decision-makers) and a wider range of potential research and decision-making questions. We organize our article according to our proposed 5 questions adapted from Alvarez et al.‘s framework: 1) what is the type of research or management question and objectives of the decision-maker(s); 2) what are the definitions of the assets to be included in the portfolio; 3) what are the ways that returns are valued, discounted, distributed and weighted; 4) what is the most appropriate way for risks to be accounted for and managed, including the selection of the appropriate model and taking into account risk preferences; and 5) what are the definitions of constraints in the programming problem.

We propose expanding Alvarez et al.‘s first question to be more broadly inclusive of the problem space in environmental research and splitting their second and third questions into three separate questions to provide further inclusions (e.g. discounting and the selection of the appropriate model). For the fifth question, Alvarez et al. (2017) provide a thorough review of the potential considerations in determining constraints to the programming problem and we do not review that question nor its considerations in detail here. Instead we dedicate more space to other previously unanswered or omitted topics, and guide interested readers to that article. While other important risk management tools exist, such as the simulation and ranking of different scenarios, adaptive models applying real option theory (e.g. Jacobsen and Thorsen, 2003) or Bayesian updating (e.g. Yousefpour et al., 2014), we here focus on methodological potentials and limitations of the application of MPT in environmental management.

Within each section (and question) of this article, we respond to considered earlier challenges noted within the broader discussion on the application of MPT. Our focus here is on novel or critical elements that should be considered in the context of each framework question; encouraging interested readers to also read those earlier articles to develop a broad understanding of this method and its nuances.

1.1. A brief summary of our approach

Using both ISI Web of Knowledge and Google Scholar in 2016 and 2017, we searched for the following terms: “portfolio theory” OR “natural capital”

“markowitz” “forest/agriculture/crop/fish”

“mean-variance” “conservation/biodiversity/environment/ecosystem”

That resulted in 741 catches, of which we reviewed 95 MPT related articles with empirical applications to environmental asset management questions

Only those articles where the explicit use of MPT was underlying the methodological framework were reviewed. We included supplementary articles throughout our analysis, from within the MPT literature and in related fields of study, to respond to specific points outlined under Sections 3-7. The review forms a core component of the following sections.

2. What is the type of research or management question and objectives of the decision-maker(s)?

The most common applications of MPT in environmental research have been in the agriculture and forestry fields of study, which have largely focused on questions of economic return and risk from the perspective of investing in specific land use or management regimes as environmental assets – also in combination with investment in other financial assets – to create diversified real asset portfolios. Recently there has been a shift in research focus away from such questions towards environmental diversification benefits and a broader spectrum of environmental assets, such as genetic and ecological diversification to enhance ecosystem resilience. The flexibility of the method is inherently linked to its advantages as a guidance tool; the fact that no single-best option is presented but that rather the whole set of scientifically derived opportunities is given (see Mallory and Ando, 2014). Upon reviewing the current literature, we have identified six research or management approaches and question types that demonstrate the evolution of MPT's use in answering questions related to sustainable environmental asset management, see Table 1.

Initially and primarily, MPT was applied at the local or site level to determine the benefits associated with the diversification and hedging of management activity portfolios (Type 1) for a single or group of decision-makers. Early studies found numerous benefits from applying MPT to diversification questions, including, but not limited to, agricultural inventories, crop allocation alternatives, and forward and

[1] See Samuelson (1983) for a comprehensive overview of von Thünen's theory.

Table 1
Main trends in the research or management approaches and question types applying MPT in environmental decision-making.[a]

Research or Management Approach and Question Type	Fields of Study Applied	Basis of Return	Basis of Risk	Examples of Decision	Examples noted in this study
Type 1: Management activity portfolios	Agriculture, Forestry, Fisheries, Conservation	Financial return	Price and Yield	Determine area allocated, number of contracts, types of species, length and location of fishing trips	Barry and Willmann, 1976; DeForest et al., 1989
Type 2: Mixed asset portfolios	Agriculture, Forestry, Conservation	Financial return	Price and Yield	Allocation of farmland, commodity futures, timberland, payment for ecosystem service schemes in mixed asset portfolio	Mills and Hoover, 1982; Perruso et al., 2005; Beinhofer, 2010
Type 3: Harvest timing portfolios	Forestry	Financial return	Price	Timing of the optimal harvest	Baldursson and Magnússon, 1997; Reeves and Haight, 2000
Type 4: Environmental risk management portfolios	Agriculture, Fisheries,	Activity intensity	Biotic and abiotic disturbances	Mitigation of invasive species, flooding damages, and yield losses	Crowe and Parker, 2008; Ando and Mallory, 2012
Type 5: Environmental valuation	Conservation	Financial return	Price	Valuation of payment for ecosystem service schemes, prevention of deforestation	Knoke et al., 2011; Matthies et al., 2015
Type 6: Genetic variation and genetic diversification portfolios	Agriculture, Forestry, Fisheries	Financial return, Ecological return	Price, survivability, yield	Prevent loss of milk production, optimal yield, ecological diversity retention, prevent population collapse	Schindler et al., 2010; Griffiths et al., 2014

[a] Applications associated with CAPM are not included in this table.

credit contracts (see e.g. Heifner, 1966; Johnson, 1967; Scott and Baker, 1972; Barry and Willmann, 1976; Buccola and French, 1977). The negative correlations of environmental assets with other available financial asset classes (e.g., stocks, bonds, commercial real-estate) demonstrated financial diversification benefits of such environmental assets as investments (e.g. Conroy and Miles, 1989; DeForest et al., 1989; Thomson, 1992). Many of these applications demonstrated the positive use of MPT in guiding more optimal diversification-based decisions across environmental management questions. Still, challenges of applying MPT in such a decision-making context remained, mainly: applications to non-linear production yields, indivisibility and illiquidity of alternative options in environmental decisions, and the variance being split over both the price and yield components as part of the expected returns (Robinson and Brake, 1979).

In consideration of issues such as indivisibility of options in environmental decisions and non-linearity in production, studies of mixed asset portfolios (Type 2) and harvest timing portfolios (Type 3) have made comparisons between land-uses and within land-uses at both the local and landscape levels. Comparisons between agriculture and forestry options have demonstrated the benefits of considering multiple land-uses as they are often uncorrelated and provide a good hedge against the high inflation associated with financial assets (e.g. Mills and Hoover, 1982; Blandon, 1985; Waggle and Johnson, 2009). Relaxing indivisibility within land-uses has been considered by looking at variables such as production and species mixes, among others (e.g. Lilieholm and Reeves, 1991; Knoke et al., 2005; Perruso et al., 2005; Neuner et al., 2013). Reductions in environmental risks have been shown to potentially outweigh lower returns associated with diversification, with benefits coming from the differing growth rates, economic rotation ages, market prices, and survivability of diversification in management decisions. Considerations for differing environmental risks within land-use types and management units have noted overall reductions in risk associated with the low correlations of returns between species (e.g. Beinhofer, 2010). Harvest timing portfolios have looked at how diversification benefits could be achieved across multiple time periods and spatial scales. Greater diversity of harvest attributes, such as locations in fishing and timing in forestry, have been found to positively affect diversification benefits (e.g. Oglend and Tveteras, 2009). However, such diversification benefits are often geographically contingent, and subject to non-systematic risks not faced by other investments (e.g., natural disturbance risks - snow, storm and insect damages) and correlations between individual assets (e.g., market prices and cohorts or rotation ages for different species) (e.g. Thomson, 1987; Caulfield, 1998; Baldursson and Magnússon, 1997; Reeves and Haight, 2000).

Since Robinson and Brake (1979)'s early commentary, further questions have been raised concerning the use of MPT to address emergent risk considerations and applications to include non-market values in the context of global change dynamics (e.g. biodiversity loss and climate change). Biodiversity, as a concept, is inherently a portfolio of species, genes, and ecological communities that respond to internal and external stimuli, which affect the distribution and proportion of each element over spatial and temporal dimensions (Figge, 2004; Harrington et al., 2010). Inquiries for applying MPT in biological conservation questions began in the 1950s, with suggestions (e.g. by MacArthur, 1955; Elton, 1958) that a stability-diversity relationship existed within complex landscapes and ecosystems. This relationship supposes that diverse ecological communities are more stable, which includes their resilience under their natural disturbance regimes (i.e. abiotic and biotic disturbances) (Doak et al., 1998; Tilman et al., 1998).

To address these questions, environmental risk management portfolios (Type 4) and environmental valuation portfolios (Type 5) have been increasingly applied. Edwards et al. (2004) suggested that the use of the 'prices and revenues only' MPT approach to indicate the optimal risky portfolio negates the risk of current actions on future harvesting opportunities (i.e. stock depletion or degradation). Those authors used a multi-species management portfolio approach that balanced between biomass and other species attributes through subtraction, to balance expected returns and variance while concurrently accounting for institutional harvest objectives and questions of biological and ecological protections. Such approaches to MPT are critical for establishing sustainable management of population dynamics and estimating optimal sustainable harvest levels over time. Crowe and Parker (2008) evaluated the structural diversity of forests in the context of climate change adaptation and species selection, indicating that optimal species portfolios of specialists better account for climatic uncertainty than generalist species. Ando and Mallory (2012) and Mallory and Ando (2014) studied conservation planning, noting that spatial trade-offs and monetary valuation techniques can have important implications for optimal allocation of conservation portfolios. They indicated that when the relationship between the estimated value and quantity of ecosystem services is non-linear, then valuation techniques are especially influential to the result. Incorporating non-market valuations in MPT applications has also provided guidance on the internalization of environmental externalities through questions of optimal land-use diversification,[2] measurement of uncertainty in non-market valuations and assessment of the trade-offs from participating in different ecosystem service compensation schemes (e.g. Knoke et al., 2011; Akter et al., 2015; Matthies et al., 2015).

Genetic variation and genetic diversification portfolios (Type 6) specifically expand the application of MPT into questions relevant to the resilience of biodiversity under risk. Initial investigations, such as Schneeberger et al. (1982), who looked at dairy sire breeding plans, have noted only the effect of genetic selection on expected incomes with MPT. However, later questions focused more on the role of diversity in temporal stability (e.g. Lehman and Tilman, 2000; Koellner and Schmitz, 2006), showing that diversity increases temporal stability at the community level and decreases it at the population level. Population synchronization[3] can lead to increases in inter-population covariance and reductions in portfolio variance for some species, while intact landscapes (i.e. limiting anthropogenic impacts like dams) can lead to higher portfolio performance overall (Moore et al., 2010; Griffiths et al., 2014). Schindler et al. (2010) noted that diversity (heterogeneity) within populations led to lower variability and lower risk of population collapse.

All of these studies indicate that broadening the use and application of MPT, to consider a wider range of risk and returns, leads to new approaches across a greater number of research or management questions within the current sustainability paradigm. They also indicate that, when it comes to portfolio selection, not only is information on an individual decision-maker's objective needed, but also information on the type of research or management question and, in some cases, the objectives of a broader set of decision-makers. Our summary shows that important advances have been made during the last two decades to adjust selection criterions from the financial market context towards greater emphasis on environmental returns and risks (see Table 1).

In summary, the trend in applying MPT is clearly towards greater considerations for environmental risks and questions focusing less on determining the optimality of a given asset class and towards those focused on the benefits of environmental diversity. Therefore, the research or management question should be framed carefully in conjunction with defining the assets and the approach (see Sections 3 onwards). As environmental questions focus less on optimality of an asset class and more on the benefits of environmental diversity, a greater assessment of benefits and beneficiaries may also necessitate considerations for more than a single decision-maker and their objectives at varying scales of decision-making. Landscape level decisions are increasingly common, but remain complex, and require different considerations[4] (e.g. such as greater integration of spatial considerations) (see Section 3). Focusing on single decision-makers or a poorly framed question can lead to sub-optimal results in many planning contexts. Thus, this forms a critical first question and consideration. However, review of question types clearly indicates that diversification benefits can change according to market, geographic, environmental or decision contexts or conditions. Penttinen and Lausti (2004) and Hildebrandt et al. (2010) highlighted the challenge of establishing ubiquitous findings (for Type 1 and 2 respectively) across all studies, geographies and contexts. Given that Type 1 and 2 questions have a greater volume of research and longer history of applications of MPT, the results for those questions are informative to guide researchers towards these considerations when applying MPT to questions under Types 3–6. To support more accurate assessments that include multiple decision-makers over larger decision contexts, further research into decision preferences and their associated trade-offs and impacts on valuations per asset quantity is needed.

3. What are the definitions of the assets to be included in the portfolio and how are they weighted?

Alvarez et al. (2017) considered that any natural capital assets that produce ecosystem services of any category should be considered as “natural assets”, setting a broad spectrum of future applications for MPT. Quantification of expected returns, and therein risk, from a given environmental asset or because of a environmental management action requires that individuals and/or society more broadly derive a benefit from it that may vary over temporal and spatial scales. This drives the definition or definitions of the asset(s) considered, as an “asset” may be defined differently according to the number and type of decision-makers, in the research or management question and the context of the decision (i.e. for conservation management versus profitability of different land-uses).

Market prices of outputs have traditionally been used to calculate the return in ecological investment and management for defined assets (Milliken and Cubbage, 1985), but other benefits from traditionally non-market sources (e.g. hiking and biodiversity) have also been increasingly considered (Mallory and Ando, 2014). In our review we find that assets, and thereby expected returns and variance of those returns (i.e. risk), can be defined by some or all of the following four key return components: a) access/ownership to the resource base/asset (e.g. land) (Barkley and Waggener, 1980); b) biological growth component (i.e. periodic growth increment); c) growth in the unit value of the output of the asset (i.e. transitions between timber assortments); and d) changes in value (i.e. monetary or non-monetary) associated with the asset (Mills and Hoover, 1982; Mills, 1988; Zinkhan and Mitchell, 1990). In the case of some question typologies, only some of these components will hold.

In association with the definitions of the assets, the question of how to assign appropriate portfolio weights is critical for determining both local and landscape level recommendations and linked closely to the definitions of the assets to be included. Optimal weights in MPT are computed as a proportion of initial capital invested into each management option, which requires sound information on the investment into each considered option to be derived. However, due to the spatial and temporal variation and the inclusion of non-market goods, this may not be an appropriate measure. Therefore, in many environmental asset

[2] Defined as the consideration for a given optimal risky portfolio that consists of different and simultaneous land use options, which are perceived as being both controlled by financial forces and inherently risky natural assets.

[3] Synchrony of population dynamics is defined by Moore et al. (2010) as a naturally and anthropogenically driven process based on three mechanisms: (1) the spatial coherence of environmental drivers, (2) spatial distribution among populations, and (3) interaction with other synchronized species. Asynchrony is maintained through diversity of phenotypes and variance of environmental conditions at the local scale.

[4] Note that this precipitates discussions on how multiple objectives are handled within an MPT framework, which we acknowledge are not covered in this article and require further discussion and research.

Table 2
Comparison of area and value weighted portfolios (time t = 0 to 1) for 14 hypothetical tree species, covering an equal portion of the forest estate (artificial data).

Species	Area proportion	Value proportion	Market value t = 0	Market value t = 1	Periodic return (%)	Return weighted by area	Return weighted by market value at t = 0
1	0.0714	0.0719	6761	7687	13.69	0.9781	0.9846
2	0.0714	0.1236	11626	11796	1.46	0.1045	0.1809
3	0.0714	0.0403	3786	4553	20.27	1.4479	0.8161
4	0.0714	0.0914	8591	9398	9.40	0.6714	0.8587
5	0.0714	0.0505	4747	6192	30.43	2.1735	1.5362
6	0.0714	0.0440	4138	4555	10.07	0.7196	0.4434
7	0.0714	0.0699	6576	7216	9.73	0.6950	0.6805
8	0.0714	0.1180	11098	10836	−2.36	−0.1688	−0.2788
9	0.0714	0.0436	4097	3591	−12.36	−0.8827	−0.5385
10	0.0714	0.1269	11935	12241	2.56	0.1831	0.3254
11	0.0714	0.0556	5228	5221	−0.13	−0.0091	−0.0071
12	0.0714	0.0827	7781	7819	0.49	0.0347	0.0403
13	0.0714	0.0425	3996	4566	14.25	1.0176	0.6055
14	0.0714	0.0391	3673	4056	10.43	0.7447	0.4072
					Mean	**7.7095%**	**6.0542%**

management questions, it will be biophysical units to be allocated that is used as weighting approach, e.g. area proportions, rather than financial capital. Especially where environmental portfolios are considered and optimized in isolation, careful consideration should be made when biophysical units are used as portfolio weights to aggregate relative returns for various assets (Mills and Hoover, 1982; Weber, 2002, p. 86). This calculus may result in incorrect average returns, for example if applied to questions of optimal land-use allocation (see Table 2).

A key driver in defining assets and their weights is often data availability and quality. These data features affect the stability of the result from optimization under MPT, which is a relevant problem for many applications to environmental problems. This may be one reason why MPT in environmental management has so far largely remained a scientific tool. Obtaining reliable data on return covariance of all possible asset combinations is critical for result stability, but information on covariances that will hold true for future developments of market and biophysical risks is almost impossible to obtain (e.g. land prices under climate change). Consequently, practitioners often abstain from creating portfolio optimizations in environmental decision-making because their results may be highly variable (e.g. Goldfarb and Iyengar, 2003).

In response to such problems with the availability of appropriate data, Richardson et al. (2000) have developed a practicable method to simulate multivariate empirical probability distributions for farm-level risk assessment. This method applies particularly when empirical data is scarce and retains as much of the empirical distributions as possible, for example the relevant intra- and inter-temporal correlations. However, the problem of possibly constructing a different future development in the data compared to historical data still remains.

A way to overcome that issue is to use a less data demanding approach that provides highly diversified portfolios proposed by Knoke et al. (2015). That approach was formulated as a variant of robust optimization (Ben-Tal et al., 2009), which considers future uncertainties by means of possible deviations from the nominal return. Maximizing the objective function is conditional on meeting an inclusive set of constraints, which control the achievement of predefined return thresholds for all considered return perturbations and portfolio options. Compared with portfolios generated with MPT, the non-stochastic alternative produced greater portfolio diversification with only moderate expected economic loss of the robust portfolios. However, Shah et al. (2017) have demonstrated that this type of "information retreat" in the context of probabilities may not be necessary. They note that algorithms can be developed to inform fine-scale planning decisions. Therefore, to increase applicability of MPT in environmental management, looking for improved alternatives in the spirit of MPT appears both promising and challenging, demonstrating the need for further applied research.

In summary, data availability and quality are critical underlying factors that guide the selection and definition of assets and their weightings. However, the definitions also drive weighting. Optimal weighting should consider whether biophysical or financial units are more appropriate. This is determined by what return components are used to define the asset or assets considered in the portfolio optimization.

4. What are the ways that returns are valued, discounted, and distributed?

Quantifying the return component for MPT application has been discussed extensively in earlier studies, but three major methodological challenges have been noted to arise in the context of environmental asset management questions: 1) temporal accounting for natural capital production periods (i.e. rotation of biological growth) and the associated financial capital requirements (Mills, 1988) (see comments from Ando and Shah, 2016); 2) the valuation of non-market ecosystem services and values (see comments from Mallory and Ando, 2014); and 3) the question how to define asset weights (see comments from Alvarez et al., 2017, and our discussion in Section 3). We provide responses below to the first two challenges.

In accounting for and quantifying temporal aspects, specifically financial returns, in the context of MPT and environmental assets, the most commonly used indicator is discounted expected returns or Net Present Value (NPV). NPV is a standard measure of return in economics to value assets as the expected value of all future cash flows. Consistent with this definition, Markowitz's (1952) original publication of MPT and numerous environmentally-based applications have used NPV of future money flows to quantify financial return (e.g. Dieter et al., 2001; Knoke and Moog, 2005; Raes et al., 2016). To solve problems of allocation concerning land or access rights, the decision variables or portfolio weights are the proportions of area allocated to each of several land- or water-use options (see Macmillan, 1992, for an agricultural example). An alternative is to use the proportions of capital invested as the decision variable (discussed later in this section), which is more consistent with the typical MPT approach from finance but seldom used in environmentally-based applications.

Combining NPV with portfolio optimization can be problematic, as doing so requires the combination of a multi-period calculus (the NPV component) with a one-period MPT model. This has been criticized by Kruschwitz (2005, p. 389) in the context of applying CAPM to estimate a firm's cost on capital. How important this aspect is though, is dependent on the nature of the underlying risk used in the MPT analysis. A potential alternative to NPV is the Internal Rate of Return (IRR) (i.e. the discount rate where the NPV of a given asset is equal to 0), which is

Table 3
Example of forest performance indices for German tree species (Weber, 2002, p. 71) contrasting arithmetic and geometric mean as estimates for the expected return.

Tree species	Oak		Beech		Spruce	
Year	Index (%)	Return (%)	Index (%)	Return (%)	Index (%)	Return (%)
1950	100		100		100	
1951	127.6	27.6	107.2	7.2	108.2	8.2
1952	152.8	19.8	150.3	40.2	159.8	47.7
1953	131.1	−14.2	154.6	2.9	183.1	14.6
1954	126.7	−3.3	150.9	−2.4	179.7	−1.9
1955	167.5	32.1	203	34.5	223.3	24.3
Arithmetic mean		**12.40**		**16.48**		**18.58**
Geometric mean		**10.87**		**15.21**		**17.43**

regularly used to quantify financial return (e.g. Fama and French, 1993). Several environmental studies simulate this by constructing appropriate indices (Mills and Hoover, 1982; Weber, 2002; Hyytiäinen and Penttinen, 2008). However, the use of IRR in the context of MPT can be problematic: averaging IRR data, when the return is formed by the quotient change in stock value over the initial stock value, does not necessarily result in the same result as the average of the annual IRRs.

The resulting difference, between the arithmetic (i.e. average IRR) and geometric (i.e. $(\text{Index}_{\text{End}}/\text{Index}_{\text{Start}})^{(1/T)}$-1) means, shows that temporal differences in time series data are biased for arithmetic outputs compared to the more suitable geometric means (Table 3). Thus, to form estimates for the expected return as used in MPT, an indicator constructed on a geometric rather than an arithmetic mean should be used.

Discounted benefits for biodiversity or ecological assets, such as genetic resources, coupled with the appropriately discounted indicators for each cohort and the asset weighting approaches are one way to achieve temporal management of data in a more robust manner in the context of environmental management risks.

The selection of an efficient discount rate is tricky under uncertain future risks and in the context of a broader set of benefits from the asset (e.g. climate regulation and timber benefits both versus only timber benefits). The question reflects either individual or a balance of preferences, market or social considerations. A decreasing time preference by the decision-maker(s) will be associated with an increasing discount rate, which reflects their utility from future benefits (or future generation's benefits). Some authors (e.g. Weitzman, 2001) argue for low discount rates to weight long-term benefits relatively higher are appropriate. Others, such as Gollier and Weitzman (2010) and Arrow et al. (2013), argue for a declining discount rate to better reflect the increasing importance of future benefits in an increasingly uncertain future (i.e. to internalize the risk of major global change dynamics like global climate change or mass extinction). Loewenstein, and O'Donoghue (2004) reported empirical discount rates of −6% to 96,000% in the context of biodiversity loss, while a precautionary approach to balancing between the preferences of current and future generations may indicate even a declining negative discount rate is appropriate given our increasing trend towards exceeding numerous planetary boundaries/thresholds resulting in irreversible future states (see e.g. Steffen et al., 2018). However, it is currently unclear how these recommendations fit within the context of environmental research and planning using MPT (TEEB, 2010, provide an extensive discussion on discounting in relation to biodiversity loss). Therefore, further investigation and study to guide appropriate discounting in the context of these new forms of risk and return is required.

An alternative approach to including temporal accounting is to look at the liquidation or market value of the asset – from the logic that the market price reflects the discounted net future production possibilities, including risk, from all marketed benefits (e.g. Prattley et al., 2007; Yemshanov et al., 2014). This market valuation approach has been used by Thorsen (2010), who calculated the annual return relative to the property value providing an estimate for those prices. However, this approach may be problematic for management systems with very uneven distribution of maturity (e.g. an uneven age class distribution in forestry) as shown by Hyytiäinen and Penttinen (2008). In that case, this approach to valuing the returns may not properly account for early-stage values and may lead to sub-optimal recommendations. Hyytiäinen and Penttinen (2008) suggested using the measure of means of the discounted net returns (i.e. NPV) to mitigate these sub-optimal outcomes.

There is also a challenge of including non-market benefits. Troell et al. (2014) noted that MPT is largely indifferent in the internalization of environmental externalities, as the valuation of such assets or their management is reflected in the restrictions of applying MPT. Still, internalizing non-market benefits into planning solutions can help to alleviate misalignments between the socially and privately minimum thresholds and optimal levels of benefit delivery (Engel et al., 2008; van Noordwijk et al., 2012). Thus, if non-marketed outputs and their associated risks are appropriately valued they can be incorporated into optimal portfolio selection.

Classical valuation studies looking at non-market benefits have often focused only on the benefit side (e.g. Finger and Buchmann, 2015); thus, ignoring the costs. However, Mallory and Ando (2014) suggest using valuations based on benefit-cost ratios rather than such a "benefits-only" approach. High correlations between ecological return values (benefits) and the opportunity costs of conservation (costs) can minimize the risk to ecological returns per unit of investment, while any changes in the opportunity costs of conservation (i.e. land values) relative to the ecological return values can result in differing optimal portfolios compared to the "benefits-only" approach. Therefore, inclusion of both benefits and costs is critical for guiding efficient diversification decisions and ensuring that "bargains" are integrated to the optimal solution.

When market prices are non-existing, non-market monetary valuation can also be used to elicit a price for a given benefit. However, such approaches still require further consideration and considerable investigation.[5] There are a number of reasons for such caution. Many non-market valuation studies still only addresse values for the general

[5] Obtaining too high estimates due to hypothetical bias is a well-known problem with many such non-market benefit valuation methods. There have been numerous examples of how handle this, which are discussed within the MPT literature. For example, Mallory and Ando (2014) considered ecological and economic returns as a linear function so that optimal solutions were indifferent to either index. Such linearity of ecological and economic returns is considered a goal in achieving efficient market pricing solutions for non-market benefits (Kemkes et al., 2010). Alvarez et al. (2017) alternatively suggested that the rules used to assign values to returns for environmental assets be adherent to the strong monotonicity assumption of consumer preference theory: where larger values are assigned to assets that are perceived to be more valuable, and larger risk scores to assets deemed riskier. These are only two examples of how to address this challenge, and we do not exhaustively cover this issue here. Rather we present it as a footnote to highlight that the issue is pertinent in the application of MPT.

public and are therefore mainly relevant in a social planner perspective – less so for individual land owners. Further, they often do not fully take risk into account. Several recent studies have shown that risks may considerably affect the values attributed to non-market benefits (Glenk and Colombo, 2011, 2013; Lundhede et al., 2015; Matthies et al., 2018, Facciolo et al., 2018). Assigning values to returns and risks may also carry inherent biases in the planning solution (e.g. whether it internalizes the risk in the discount rate, see discussion on discounting earlier in this section, or to the expected returns, and the extent to which risk is considered – i.e. one or many risk(s), and their inter-related nature); thus, the benefits of portfolio optimization as a planning method may be limited for such planning contexts. Divergences between the elicited values for a benefit and the environmental benefit index value itself may also result in highly divergent portfolio solutions. For example, the value gap in contingent valuation approaches is well-documented and often exceeds the expected level of difference between the two elicitation methods (see e.g. Horowitz and McConnell, 2002). Therefore, certain optimal solutions may be over or underweight a given "asset" based on the value prescribed resulting from an inherent disparity, upward or downward bias, in the attributed benefit value. This is counter to the assumption of a linear function, considered by Mallory and Ando (2014), suggesting that such an assumption may not hold between elicited monetary valuation approaches. These nuances to monetary and non-monetary valuation underscore the potential challenges of integrating such values to the optimisation problem.

In those cases where there are emergent markets for previously non-marketed benefits (e.g. recreation, carbon or biodiversity markets), integration of market values should still be done carefully – both due to the impact that underlying factors (e.g. compliance-based regulation, subsidies, market supply restrictions or non-transparent market pricing) may have on the optimality of different options and due to the importance that optimal solutions may have in guiding decision-making. Engel et al. (2015) indicated that socially-efficient pricing for many non-market benefits should be correlated with the opportunity costs of conservation. However, in the context of MPT such correlations are likely to lead to sub-optimal portfolios for those decision-makers (e.g. households) that rely on diversification as a hedge against extreme risk events (e.g. climatic impacts). As market prices for previously non-market benefits are often initially set by policy makers or technocrats, they may also capture pricing inefficiencies, such as information rents (e.g. Juutinen and Ollikainen, 2010). Therefore, it is important to consider how emergent pricing mechanisms are included and their time series integrated into MPT solutions. In some cases, synthetic proxy values can be used to integrate market pricing for such benefits; especially those that have limited availability of market data over the required time series. However, this may artificially improve or reduce the risk-reward ratio for those benefits (see e.g. Matthies et al., 2015). These challenges can be overcome though various techniques to deal with limited data discussed in Section 3.

Irrespective of the definition of risk (variance or downside risk measures) that is used, when building portfolios, usually a normal distribution is assumed (with the exception of Poisson-based approaches mentioned in the next paragraph, Fasen et al., 2014). Smith and Hammond (1987) have shown that MPT is rational under the assumption of normally distributed returns. Nevertheless, this requirement is hard to achieve in real applications, where the actual distribution of returns is unknown or where the variance is derived from several sources and transformed in non-linear ways into an economic return measure (Yu and Jin, 2012). To solve this problem, techniques such as Monte Carlo Simulation may be applied (e.g. Knoke and Wurm, 2006). Yet, it does not solve the issue of intertemporal variance (see also suggestions on how to derive multivariate empirical probability distributions by Richardson et al. (2000)).

To be applicable in MPT studies, it is very advantageous that the return distributions of the single mixed assets be approximated by functions, so that the expected means and return variabilities may be combined according to allocated proportions. An alternative approach would be to pre-define discrete types of mixed assets and to evaluate their simulated distributions, independent of the distribution types. This would, for example, be possible with Stochastic Dominance rules (e.g. Benítez et al., 2006; Hardaker et al., 2004). The land-use alternatives to be ranked in a stochastic efficiency (Hardaker et al., 2004) context, can be defined by decision-makers or scientists (Monge et al., 2016). However, comparing pre-defined discrete combinations of assets would risk the exclusion of the optimal combination. Excluding such options, in the context of global change dynamics and risks, even if they may appear infeasible from a practical perspective, would be counter to the aims of such risk assessment, planning and management to identify trade-offs. A substitute approach would be to estimate expected utility under higher-order moments for portfolio selection. Acevedo (2015) refuted that option by showing that the results of land-use portfolios derived to achieve maximum utility under higher-order moments hardly differ from those derived under the assumption of normally distributed returns. Their result may be an effect of the central limit theorem, which says that the distribution of statistical sums or averages of variables always converges towards a normal distribution if the summed/averaged variables are random and independent. The resulting distribution of aggregated portfolio returns could be normal, although the return distributions of the single assets are not. Nevertheless, when extreme values come into play, or if the combined assets are too closely correlated, even the aggregated distribution of portfolio returns may not be well approximated by means of a normal distribution. In such cases, Poisson's classic theorem on rare events may actually be a better choice than Gauss' normal distribution to model portfolio returns (Fasen et al., 2014). However, applications of MPT in environmental studies that account for these issues are still too rare, at least so far.

It is important to note that, despite the drawbacks associated with the required normality of return distributions, MPT can still be a helpful tool for estimating efficient sets as a basis for the maximization of expected utility (Ames et al., 1993). Meyer (1987) pointed out that the mean-variance rule can result in an efficient ordering of risky assets or projects, when the distributions being compared belong to the same class and differ only in location and scale parameters (where μ and σ are the parameters), making it similar to second-order stochastic dominance ordering (Moschini and Hennessy, 2001).

In summary, returns should be considered carefully, including: how economic and environmental returns are integrated (or not), the appropriate monetary or non-monetary valuation techniques used, how to use weighting, and whether and how to use discounting and the appropriate discount rate. Much of current environmental benefits are non-marketed and instead appear as an externality to monetized outputs. However, as these benefits are increasingly internalized to MPT decision problems, through the valuation of the benefit components driving returns, the same consideration as applied to already monetized benefits will apply. We highlight a number of considerations in the context of monetizing benefits, but do not provide an exhaustive discussion. Critical research into how best to integrate these returns into portfolio analysis is needed, but also further understanding of the implications for discounting and weighting. Further research considering how to handle indivisibility and illiquidity of alternative options and applications of Poisson's classic theorem in replacement of Gauss' normal distribution are also needed.

5. What is the most appropriate way for risks to be accounted for and managed, including the selection of the appropriate model and taking into account risk preferences?

Classical portfolio optimization derives an efficient frontier formed by portfolios (mixed assets), which maximize the economic return for a combination of assets given different levels of economic risk ("mean-variance" optimization). Diversification usually leads to lower variance and greater expected returns with a portfolio of assets, when compared to a single-asset. Uncertainty is addressed by reducing exposure to unsystematic risk through exposure to multiple assets, a fully diversified portfolio creates a trade-off between expected return and unsystematic risk – otherwise known as the *efficient frontier*. To date, most environmental studies applying MPT utilize variance of the expected portfolio return as a measure for risk. However, variance[6] may not be an appropriate measure for risk in the context of such questions as it contains both negative and positive deviations from the expected return.

Deviations in returns are sometimes desired rather than be avoided when considering questions of ecological resilience. Alternatives to variance are the use of semi-variance or indicators which combine financial return and risk into one index (e.g. lower partial moments (LPM) or Value at Risk (VaR)). These measures punish deviations below a defined threshold more than valuing options above this threshold (i.e. a symmetric risk measure). LPMs of first and second order account for the portion of total value that fall below a predefined threshold. This can be suitable when focusing on extreme but rather rare events (e.g. climate change, see Ramirez et al., 2001). When applied to pre-defined options, LPMs result in an ordering of options similar to a stochastic dominance approach for a set of selection criteria. Downside risks can, however, become difficult to calculate when comparing portfolios instead of single assets (Grootveld and Hallerbach, 1999). Shah and Ando (2015) recently suggested that building portfolios based on LPM may lead to substantially different portfolio allocations than approaches that use variance as the risk measure in conservation planning. This was particularly true for situations with skewed distribution patterns (see also discussion of return distributions in Section 3).

Elton et al. (2007) argued that, for well-diversified portfolios, choosing either semi-variance or variance will not change portfolio selection, and Grootveld and Hallerbach (1999) used empirical data to show that portfolios built in a Mean-LPM framework hardly differed from those of a mean-variance model. If the distribution of only some individual assets are skewed the multivariate distribution may follow the Gaussian model, but the use of a mean-LPM2 framework may still actually be favourable to a mean-variance model if the decision-maker is particularly averse to deviations below a certain threshold (Shah and Ando, 2015). This situation is common in environmental planning, where rare and extreme events are considered (see e.g. applications by Berbel, 1988; Ramirez et al., 2001; Shah and Ando, 2015).

Catastrophic outcomes mean that the research or management questions and the selection of appropriate measures to account for risk should be carefully assessed and should aim to avoid target shortfall (i.e. unwanted outcomes). Consideration of selection criteria developed by Roy (1952), Kataoka (1963) and Telser (1955) (also called the *safety-first models*) should be made by the researcher(s) or planner(s). Safety-first models have appeal for environmental questions, as these typically suffer from extreme, discontinuous risks (Dunkel and Weber, 2012; Fasen et al., 2014). Often applied in agricultural economics (Bigman, 1996; Jakoby et al., 2014), they can also be useful for calculating stochastic replacement costs for carbon sequestration in forests (Gren and Carlsson, 2013). Baumgärtner and Strunz (2014) have encouraged further application in ecosystem resilience studies. However, there is still disagreement about their ability to perform better, as a positive model, in comparison to variance. Lin et al. (1974) found that safety-first models perform as poorly as a pure "profit maximization" objective functions in explaining farmer's actual behaviour, while Moscardi and Janvry (1977) have found a high agreement of model results with reality. Further research is needed to better understand the benefits and limitations of their application.

Another important downside-risk measure, increasingly applied in environmental planning, is the quantile-based VaR (Estrada et al., 2012; Härtl et al., 2013; Sethi et al., 2014; Hahn et al., 2014; Bird et al., 2016). It represents the best outcome possible if expected returns occur within the worst part of the distribution (i.e. the left tail). It also follows the ideas by Kataoka (1963). The downside risk measure has been applied in various sectors of environmental management (Harlow, 1991), but under non-normally distributed returns it lacks some important properties for portfolio selection (e.g. subadditivity, homogeneity and monotonicity) and may also not adequately represent the benefits of diversification (Dunkel and Weber, 2012). Recently the Conditional VaR (CVaR), defined as the conditional expectation of losses exceeding VaR at a specified confidence level, has been proposed to overcome some of these limitations (e.g. Wan et al., 2015) and has been applied to questions of land and environmental management (Webby et al., 2007; Ermolieva et al., 2016; Hu et al., 2016).

LPMs of first and second order used for portfolio selection can account for the portion of total value that falls below a predefined threshold. This can be suitable when focusing on extreme but rather rare events (e.g. climate change, see Ramirez et al., 2001). LPMs result in an ordering of options similar to a stochastic dominance approach for a set of selection criteria. Mathematical advances in constructing efficient frontiers following CVaR (Wan et al., 2015), LPM (Shah and Ando, 2015) or Generalized Expected Utility mean that the disadvantages of shortfall measures for portfolio selection are potentially reducing; thus, increasing their appeal for application to environmental research or management questions (see e.g. Dunkel and Weber, 2012 Artzner et al., 1999).

The Separation Theorem of Tobin (1958) and CAPM also have been applied to aid portfolio selection in ecological economics (e.g. Sharpe's Ratio (SR), see Sharpe, 1964) for land-use allocation (Knoke et al., 2011, 2013). It represents the profitability of a given portfolio resulting from the relationship between the expected returns exceeding those from the risk-free investment. Roll (1977) stated that applications of CAPM lack the possibility of testing the results in a real world, as it is designed as a "normative model" (Roll, 1977). However, Ochoa et al. (2016) used optimizing land-use allocation in Ecuador where SR gave realistic land-use portfolios, compared to today's land-use allocation and Simmons (1999) suggested that the Separation Theorem gives a grounded theoretic explanation for farmer's attitudes towards future markets. These types of outcomes are critical to guide discussions on environmental allocations, such as those related to the relationship between deforestation and agricultural land-use. The SR has appeal particularly for environmental management applications as there is no need to quantify risk aversion which can produce comparable results for different situations and applications. We have summarized and overviewed each of these models, their advantages and disadvantages, in Table 4 below.

In the context of Type 6 questions, the permanent exclusion of some species may also be better managed with the appropriate safety-first model. To better account for the covariance effect related to the risk-adjusted performance of the environmental assets, like symbiotic species, Doak et al. (1998) and Tilman et al. (1998) have both presented differing mathematical approaches, by means of a coefficient of variation (CV) approach, to manage for this.

Depending on the definition of the asset or assets included in the portfolio, spatial variation and co-variation may also occur within or among assets. This variation often occurs according to the abundance and value of environmental benefits and is linked to the regulation of access rights (e.g. land ownership) and the environmental asset (e.g. biomass growth). It results in spatial inequalities (i.e. conservation in one area excludes access for spatially dependent individuals) that are not accounted for within MPT. Variance of returns occurring over an extended time horizon also become more pronounced if the defined environmental assets under consideration have differing time horizons (Flora, 1964). Exclusion of some asset diversity from an optimal portfolio in each year may result in an asset's exclusion permanently from all subsequent portfolios (i.e. extinction of a species or loss of genetic diversity from a population) (Figge, 2004). It has been suggested that variation in expected performance of a natural population of a given species (i.e. "assets") can be accounted for either by defining spatial variation within a set period

[6] Often expressed as standard deviation.

Table 4
Main portfolio selection criteria used in environmental applications of portfolio theory.[a]

Criterion for Selection	Explanation	Calculus (Objective function for portfolio optimization)	Advantages	Disadvantages	Examples for environmental studies
Maximizing Expected utility	Maximize the certainty equivalent (CE)	$CE = R_L - \frac{a}{2} * S_P^2$ With a defining the individual risk aversion (for example in relative terms in relation to initial investment (see discussion by Hildebrandt and Knoke (2011))	● Approximates rational decisions under uncertainty	● Absolute risk aversion i.e. individual utility function needs to be estimated ● Losses and gains are valued equally	Hildebrandt and Knoke (2011), Castro et al. (2013)
Roy's criterion (Roy, 1952)	Selects portfolio, which has the smallest probability of producing a return below some specified level	Min Prob ($R_P < R_L$) or $Max \frac{R_P - R_L}{S_P}$	● Easier quantification of risk aversion through shortfall target (see e.g. Moscardi and Janvry, 1977) ● Under non-normally distributed returns, Chebychev's inequality can be applied ● Optimal portfolio lies on efficient frontier	● Does not include magnitude of shortfall	Lin et al. (1974), Moscardi and Janvry (1977), Tessema et al. (2015), Setia and Johnson (1988)
Kataoka's criterion (Kataoka, 1963)	Maximizes lower limit, subject to the constraint that the shortfall probability is equal to or lower than some specified value Similar to Value at Risk (see below) (if monetary values are used)	Max R_L s.t. Prob ($R_P < R_L$) ≤ α or s.t. $R_p \geq R_L + \alpha_{const} * S_p$ (α_{const} is e.g. 1.65 for α = 0.05)	● Easier quantification of risk aversion through shortfall probability ● Under non-normally distributed returns, Chebychev's inequality can be applied ● Optimal portfolio lies on efficient frontier	● Does not include magnitude of shortfall ● (See also Value at Risk below)	Lin et al. (1974), Ceccarelli and Grando (1991), Moscardi and Janvry (1977), Setia and Johnson (1988)
Telser's criterion (Telser, 1955)	Maximizes expected return subject to the constraint that shortfall probability is not greater than some predetermined number	Max R_P s.t. Prob ($R_P \leq R_L$) ≤ α $R_p \geq R_L + \alpha_{const} * S_P$ (α_{const} is e.g. 1.65 for α = 0.05)	● Most frequently used in today's financial asset allocation	● Can fail to achieve feasible option	Jakoby et al. (2014), Gren et al. (2012), Gren and Carlsson (2013), Moscardi and Janvry (1977)
Lower Partial Moments (first and second order)	Calculates the magnitude of shortfall (shortfall expected value, first order) and squared deviation from target (shortfall variance, second order)	$Min\ LPM_n(R_L; f) = \int_{-\infty}^{R_L} (R_L - R_P)^n f(x)dx$ n: order of LPM (1 or 2)	● Includes magnitude of shortfall (first order) ● Gives stronger emphasis on extreme events (second order). ● Can be a helpful tool to extend other criterion.	● Correlations and diversification effects are not directly considered (only when indirectly applied using simulation techniques). ● Therefore, only leads to ordering of options rather than an optimal combination of assets.	Ramirez et al. (2001), Berbel (1988), Shah and Ando (2015)
Value at Risk (VaR)	Maximizes the expected portfolio return at a specified quantile (i.e. 1 or 5%) at the (usually) left tail of the distribution Variants: Conditional VaR (see text)	Max VaR = $R_P - \alpha_{const} * S_p$ (For normally distributed returns) (α_{const} is e.g. 1.65 for α = 0.05)	● Conservative measure, focusing on the left tail of the distribution ● Easier quantification of risk aversion	● Ignores extreme tails ● lacks subadditivity (i.e. a portfolio's VaR may be greater than the sum of the individual VaR) ● Often gives non-smooth, non-convex function	Sethi et al. (2014), Härtl et al. (2013), Hahn et al. (2014), Estrada et al. (2012), Bird et al. (2016), Conditional value at risk: Wan et al. (2015), Webby et al. (2007), Ermolieva et al. (2016), Hu et al. (2016)
Sharpe's Ratio Sharpe (1964)	Maximize Ratio between Net Portfolio Return (which exceeds return of a riskless alternative investment) and Portfolio Risk (i.e. Standard Deviation) (equals Roy's criterion if $R_L = R_R$)	$Max\ SR = \frac{R_P - R_R}{S_P}$	● No need to quantify risk aversion ● Portfolio composition is not altered by risk aversion	● Based on assumptions of CAPM (i.e. same expectations towards future, same availability and access to R_R etc., no change in value of R_R over time) ● Results depend on assumption concerning R_R	Knoke et al. (2011, 2013), Clasen et al. (2011), Hildebrandt et al. (2010), Griffiths et al. (2014), Lundgren (2005), Sandsmark and Vennemo (2007)

[a] For consistent description, we largely follow the notation where: R_P: Expected return on the portfolio, R_L: Lower target value for expected return below which investor does not wish returns to fall, S_p Standard deviation of portfolio, α = target shortfall probability, R_R: Return of an alternative riskless investment.

(i.e. referred to as biological variation due to the ability of a given species to perform ecosystem functions in differing sites) or inter-annual variations (i.e. referred to as a proxy for ecosystem stability) (Lehman and Tilman, 2000; Koellner and Schmitz, 2006).

However, Koellner and Schmitz (2006) have noted that the effects between species are often abstracted (i.e. non-interactional) by such measures in the context of MPT and follow statistical interactions only; like financial portfolios. Therefore, any changes in performance are linear; returning to the MPT critique of Robinson and Brake (1979) (see Section 2). Spatial scales for many species can also extend to the landscape level and have ecosystem-wide impacts and variations in environmental performance, equated to measures of ecosystem functioning, that occur both horizontally (i.e. within trophic levels) and vertically (i.e. between trophic levels) to provide a so-called 'insurance value' (i.e. resilience) within the ecosystem. These challenges may be difficult to adequately reflect through statistical interactions (Halpern et al., 2011; Koellner and Schmitz, 2006; Baumgärtner and Strunz, 2014). Therefore, it may be challenging to define such assets, in the context of applying MPT, if their relationships cannot be captured statistically.

Koellner and Schmitz (2006) proposed a risk-adjusted yield for different levels of biological diversity to better manage the effects of variation between species. To address issues of asset indivisibility, Lilieholm and Reeves (1991) and Figge (2004) suggest that decision-makers may count symbiotic species as a singular asset with linear interactions or define such decision variables as complete systems with an expected yield. This can help to account for the effects between species becoming too abstracted at a higher level. These suggestions are aligned with the weighted biodiversity indices proposed by Shah and Ando (2015) and demonstrate again the importance of weighting in the context of Type 6 research questions. Ando and Shah (2016) suggested another means for dealing with the challenges noted above: dynamic portfolio optimization. This can enable rebalancing of portfolios to better reflect changes between intervals over the planning horizon. However, the availability of data for such measures at higher spatial planning levels like regional or landscape makes collection of inter-annual variances challenging.

In summary, this discussion highlights the partial flexibility of MPT, as a method, in handling of risks from multiple assets or management options. Risks, including global change dynamics, can be integrated with one another to better reflect the associated trade-offs. In those cases, variance may not be an appropriate measure for risk. Solutions that consider the benefits of deviation, left-tail risks, and spatial and genetic variation demonstrate the importance of considering different models for reflecting the role of variance in different types of portfolios or research questions, but require further application and research. In that context, we broaden and extend Hoekstra's (2012) call to use of MPT in evaluating the risk-reward trade-off in conservation investments, and instead call for MPT studies to address the diversification and trade-off dynamics for a set of global change impacts at multiple scales. Further research into non-stochastic approaches and applications, the use of safety-first models and risk aversion would be supportive in building a broader application of portfolio approaches in the spirit of MPT.

6. What are the definitions of constraints in the programming problem?

We do not cover the fifth question regarding the definitions of constraints in the programming problem here in detail. Alvarez et al. (2017) provide a thorough review of the potential considerations and we refer interested readers to that article.

7. Conclusions

The discussion on how and when to apply MPT is not yet complete and requires ongoing discourse and new perspectives to ensure that it is continuously developed to robustly meet current research and management challenges and questions. Our adaptation of Alvarez et al.'s framework responds to earlier research and is part of that ongoing discourse rather than a definitive set of guidelines. The goal is to further develop a framework for applying MPT that can be used by both researchers, as well as managers and policy makers.

As applications of MPT trend towards greater considerations for environmental risks (question Types 3–6), new perspectives on diversification benefits are required. Researchers applying question Types 3–6 should take guidance on the potential implications of this from the broad literature base regarding the first two types. Outcomes from applying MPT can be highly contextual, asset definitions (which drive weighting) and weightings themselves are critical to ensuring robust results, and the manner that returns (environment and financial, monetary and non-monetary) are included should be considered carefully. In the case of monetary valuation, the inclusion of previously external benefits mean that variance may not be the most appropriate measure for risk. Solutions should consider the type of deviation that should be avoided, such as left-tail risks, and the spatial and genetic variation that are targeted.

Noted throughout this article is a call for further research. Most critical, is research into how best MPT studies can address the diversification and trade-off dynamics resulting from global change impacts occurring at multiple scales. Non-stochastic approaches and applications, the use of safety-first models and risk aversion, all point to ways that these risks can be managed. Also, decision preferences and associated trade-offs can help to indicate how returns from monetized benefits can be integrated. Still, research is needed to ensure the appropriate measures are taken when considering discounting and weighting. Finally, environmental research questions, such as Type 3–6, require more discussion on how MPT assumptions around indivisibility, illiquidity and the replacement of Gauss' normal distribution affect the results.

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Appendix A. Mean-variance model

MPT assumptions state that the optimal portfolio is preferred by all rational investors, regardless of their risk aversion, and is represented by the tangency portfolio. Investors/decision-makers only differ in the amount that they allocate between the opportunity cost of capital (i.e. risk-free rate) and the tangency portfolio. Changes in the risk-free rate lead to changes in the allocation, making determination of this rate and inclusion of temporal changes an important consideration for using MPT in decision-making. Portfolio risk is expressed by the sum of all return covariances, in the form of the portfolio variance, or as the square root of the variance, the standard deviation (Eq. (A1)):

$$S_L = \sqrt{a^T \sum a} = \sqrt{\sum_{i \in L} \sum_{j \in L} a_i a_j cov_{i,j}} \tag{A1}$$

s.t.

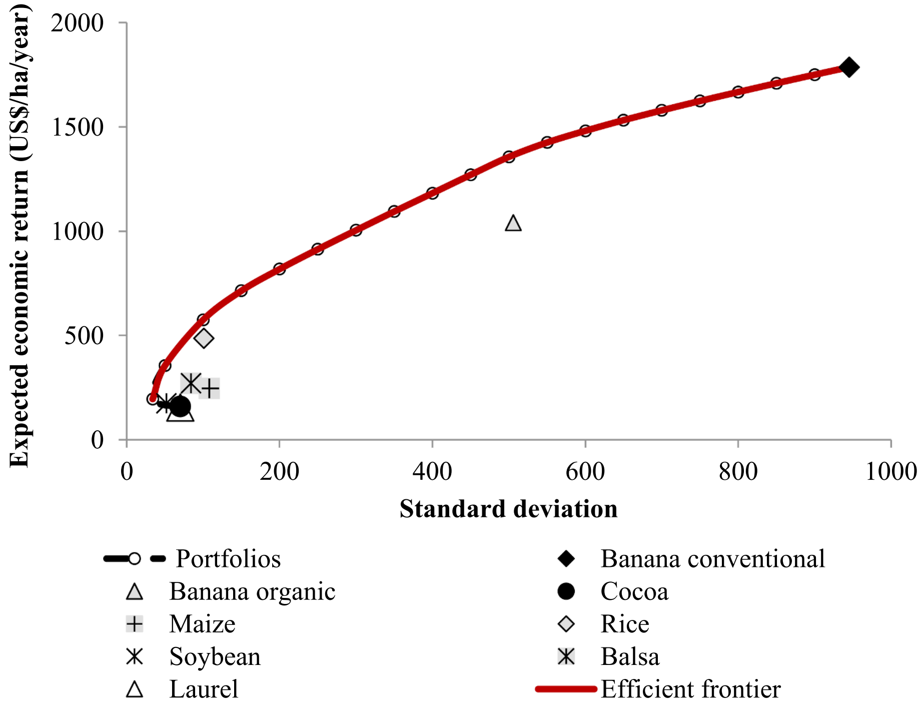
$$1^T a = 1 \tag{A1.1}$$

$$cov_{i,i} = var_i \tag{A1.2}$$

$$cov_{i,j} = k_{i,j} s_i s_j \tag{A1.3}$$

$$a_{i,j} \geq 0 \tag{A1.4}$$

where S_L is the standard deviation of the uncertain portfolio yield, $\mathbf{\Sigma}$ is the covariance matrix, $cov_{i,j}$ are the covariances of uncertain financial yields between the i^{th} and j^{th} assets (if $i = j$ then it is variance), var_i is the variance for the i^{th} asset, $k_{i,j}$ is the correlation coefficient between the i^{th} and j^{th} assets, s_i is the standard deviation for the i^{th} asset, and i, j are indices for different options. The decision variables, which are controlled by the investor (e.g. the land or ecosystem owner), are denoted by a_i. Classically a_i is the proportion of initial wealth (usually money) allocated to investment options. In MPT, variance or standard deviation of the economic return are the measures of risk (Fig. A.1). On that basis, Markowitz (2014) recently underlined that the careful choice of portfolios from a mean-variance efficient frontier will approximately maximize expected utility for a wide variety of concave utility functions, which are characteristic for risk-aversion.



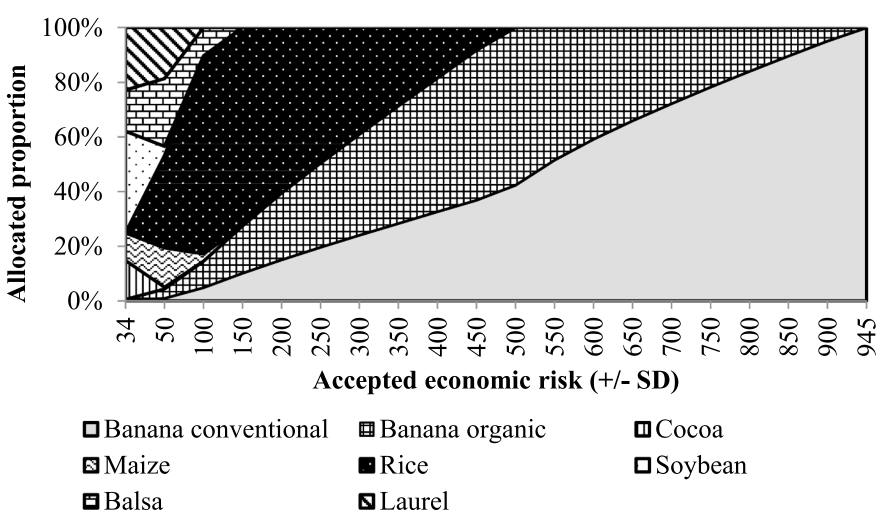


Fig. A1. Example of an efficient frontier in a mean-variance optimization (adopted from Castro et al., 2015). A) Maximum achievable return for given levels of risk (i.e. efficient frontier, compared to return and risk of single land-use options). B) Structural composition of land-use portfolios which form the efficient frontier. It is shown how much land is allocated to the available land-use alternatives for given (accepted) levels of risk to maximize the expected (annualized) net present value.

The standard deviation of a portfolio is dependent on 1) the correlation between asset pairs, 2) asset weightings in the portfolio, and 3) individual asset's standard deviations (Caulfield, 1998). The decision variables, which are controlled by the investor (e.g. the land or ecosystem owner), are the proportion of initial wealth (usually money) allocated to the different investment options. In questions of environmental management, the existence of portfolios consisting of alternative allocations, uses or groups, such as, land-uses (e.g. forestry or agriculture) or land-use management decisions (e.g. selection of species), meaning that the decision variable of invested capital is often replaced by land or other natural assets. This practice refers to von Thünen's theory (1826). Samuelson (1983) provides a comprehensive acknowledgement of Thünen's theory, which has since been combined with the theory of portfolio selection (e.g. Macmillan, 1992).

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