Portfolio analysis as a means of managing uncertainties in climate change adaptation: some initial reflections

In order to counteract the challenge of climate uncertainties in investment planning, Portfolio Analysis (PA) aggregates diverse adaptation measures in different portfolios. Thus, instead of considering a single intervention, it attempts to identify the best portfolios according to their performance in relation to economic efficiency as well as risk (variance of the economic performance over different scenarios). However, whilst PA is recognised as having the potential for bringing about a more holistic economic analysis of adaptation, it remains rarely used. Our assessment of the key strengths and limitations of PA suggests that wider adoption of a portfolio approach will primarily depend on stakeholder recognition that by being selective about the numbers and composition of portfolios considered, data and analytical capacity constraints can be overcome.

Con el fin de contrarrestar el reto de las incertidumbres climáticas en la planificación de inversiones, el Análisis de Cartera (AC) agrupa diversas medidas de adaptación en diferentes áreas. Así, en lugar de considerar una única intervención, la AC procura identificar las mejores carteras de acuerdo a su rendimiento en eficiencia económica y riesgo (variación del rendimiento económico en diferentes escenarios). Sin embargo, pese al potencial de la AC en lograr un análisis económico de adaptación más holístico, rara vez se utiliza. Nuestra evaluación sobre las fortalezas y limitaciones de la AC sugiere que una adopción más amplia en el enfoque de carteras dependerá principalmente de las exigencias de los interesados, dado que su criterio sobre el número y la composición de las carteras puede solventar las limitaciones de datos y la capacidad analítica.

Inbertsioen plangintza burutzean, klima-ziurgabetasunak dakarren erronkari aurre egin nahian, ikusi dugu Zorroaren Analisiak (ZA) hainbat egokitzapen-neurri gehitzen dituela hainbat arlotan. Beraz, esku-hartze bakar bat kontuan hartu beharrean, zorrorik onenak identifikatzen saiatzen da ZA, kontuan hartuta zer errendimendu duten eraginkortasun ekonomikoari eta arriskuari dagokienez (errendimendu ekonomikoaren bariantza hainbat egoeratan). Hala ere, ZAri egokitzapenaren analisi ekonomiko holistikoagoa lortzeko gaitasuna duela aitortzen bazaio ere, oso gutxitan erabiltzen da. ZAren indargunei eta funtsezko mugei egin diegun ebaluazioak iradokitzen du zorroaren ikuspegi zabalago bat izatea interesdunen errekonozimenduaren gorabeheran geratzen dela nagusiki; izan ere, aztertutako zorroen zenbakiekin eta osaerarekin selektiboak izanez, datuen mugak eta gaitasun analitikoa gainditu daitezke.

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1. INTRODUCTION

Adaptation measures are a challenging duty and they have to deal with the deep uncertainty which characterises the assessment of the costs of the climate change impacts and the benefits of adaptation options. The definition of effective adaptation policies thus requires the knowledge and use of new decision methods and criteria able to deal with an uncertainty called Knightian (Knight, 1933), due to the impossibility to characterise it with an objective probability distribution. Several decision tools (e.g. the Robust Decision Making and the Real Option Analysis) and new decision-making processes (such as the Iterative Risk Management or the Adaptation Pathways Approach) have been assessed in the scientific literature. These approaches have been widely assessed and described by the scientific literature.

This paper focuses instead on the Modern Portfolio Theory (MPT), another promising tool, which, despite originating from the financial sector, helps the decision-maker in identifying a set of possible climate adaptation investment solutions, including the estimate of the returns of the policies and their variability in relation to a set of possible scenarios. The decision-maker can thus aggregate diverse measures with the aim to reduce the risk connected to their performances in the future, taking advantage of an important property of the portfolio theory: the economic returns of the assets are additive, while risks partially cancel each other out (Markowitz 1952, 1956).

This paper thus discusses the main steps of the MPT methodology, reviewing and evaluating concrete applications in the field of the natural resource management and the climate change related investments. The essential goal of the paper is to identify the key strengths and weaknesses of this instrument for the definition of effective adaptation policies, reducing the variance of the return against different climate scenarios, and adequately communicating to local and wider stakeholders the risks connected with badly constructed climate change adaptation policies. This paper therefore focuses only on the essential elements of MPT, largely ignoring the data-intensive developments in the method that continue in financial market applications. Climate change uncertainty and the alternative decision support methods.

Climate change adaptation policies have been recognised as a key issue of the global development policies. They were inserted among the 17 Sustainable Development Goals (2015) with a dedicated goal: «Take urgent action to combat climate change and its impact». The Paris Agreement (2015) stated that there is a «need for an effective and progressive response to the urgent threat of climate change» and that there is an «intrinsic relationship that climate change actions, responses and impacts have with equitable access to sustainable development and eradication of poverty». Climate change is also a pillar and a cross-cutting topic of the Sendai Framework for Disaster Risk Reduction: «disasters, many of which are exacerbated by climate change and which are increasing in frequency and intensity, significantly impede progress towards sustainable development» (UNISDR, 2015).

Besides these global commitments, the public administrations also produced strategies and plans, with the aim to identify the expected impacts of climate change, the adaptation objectives and a series of adaptation measures. In the European Union, (EU), 28 European countries – 25 EU member states and 3 European Economic Area (EEA) states – have adopted a national adaptation strategy; whereas 17 of them – 15 EU states and 2 EEA states – have also developed a plan (EU, 2017). National Adaptation Programmes of Action (NAPAs) were created at Cop 7 (2001) in Marrakesh for the specific and urgent needs of the Least Developed Countries, whereas the Cancun Adaptation Framework (2010) instituted the National Adaptation Plans (NAPs)[1], with the goal to develop a more comprehensive adaptation process, with a medium and long-term approach to reduce the vulnerability to the adverse effects of climate change.

However, despite the presence of a plurality of political commitments, there is an uneven implementation of adaptation measures, as their monitoring is particularly complex because of the thin differences between the common development policies and the adaptation policies (Schipper, 2007). However, some reviews were

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1 13 plans (data updated at October 2019) have been submitted since the 2015 (Brazil, Burkina Faso, Cameroon, Chile, Colombia, Ethiopia, Fiji, Kenya, Saint Lucia, Sri Lanka, the State of Palestine, Sudan, Togo).

developed (Ford et al., 2011; Ford *et al.*, 2015; Lesnikowski *et al.*, 2015) showing the lack of a straightforward and effective implementation of adaptation policies. Three main obstacles emerge in the scientific literature: i) The presence of conflicting definitions about adaptation and a complex theoretical framework (Fankhauser, 2017; Hall, 2017; Schipper, 2007); ii) The existence of adaptation barriers (e.g. lack of economic resources, institutional failures, conflicting values) and limits (e.g. physical limits to migrations) (IPCC, 2014; Adger *et al.*, 2013; Moser *et al.*, 2010); iii) The uncertainty connected to the economic evaluation of the local impacts of climate change and of the benefits of the adaptation measures (Wilby and Dessai, 2010; Heal and Millner, 2014; Hallegatte *et al.*, 2012; Pindyck, 2007)[2]. This last obstacle is perhaps most important since it can hamper the design and the development of adequate adaptation policies. Lack of knowledge about the costs and benefits of the climate change impacts and of the adaptation options available limits the ability of traditional decision support tools (such as the Cost-Benefit Analysis and the Cost-Effectiveness Analysis) in identifying effective policy solutions.

The scientific literature has highlighted the possibility to use alternative decision support tools or decision-making processes, that are able to integrate climate change risk into economic analysis or into the decision-making process, including real options analysis (ROA) and robust decision-making (RDM). Watkiss *et al.* (2015) and Dittrich *et al.* (2016) conducted reviews about these new decision methods, focusing both on decision-making processes and decision support tools. Portfolio Analysis is one of these instruments, as it can help public or private decision-makers in identifying portfolios of measures which can be effective over a wide range of possible futures, limiting the variance of the return of the investment. MPT could be effective even for the communication of the uncertainty connected to climate change, especially by informing long-term decisions that could be highly affected by climate variations. MPT can thus help decision-makers (both private and public) in planning investments in an uncertain framework, giving them the opportunity to find ways to reduce the variability of the expected outcomes, without losing economic returns.

2. MODERN PORTFOLIO THEORY, THE THEORETICAL FRAMEWORK

MPT is fundamentally based on the seminal work («Portfolio selections») of Markowitz (1952), who started systematising some key concepts. The starting point of Markowitz's research is the broadening of the idea that the goal of the investor is the maximization of the discounted expected revenues of his investment. Investment decisions are made in a context of uncertainty about the future conditions and out-

[2] There are four main sources of this uncertainty: uncertainty regarding the trajectory and dimensions of future greenhouse gas emissions, uncertainty regarding the sensitivity of climate to GHG emissions, uncertainty regarding the range and dimensions of uncertainty, and uncertainty relating to the costs and effectiveness of adaptation responses.

comes, therefore there is no perfect knowledge about the investment revenues. The investor surely considers the expected revenues as a desirable thing, but he looks also at the variability of this amount according to the plurality of possible futures. The aim of the investor, and the reason why he decides to diversify his investment in a portfolio, is the maximization of the expected return given his tolerance of risk. Alternatively stated, an investor seeks to minimize the risk at which he is exposed given some target expected return (Fabozzi, 2008; Aerts *et al.*., 2008; Watkiss *et al.*, 2015; Francis and Kim, 2013).For the reasons given above, MPT has been widely used in other fields beyond the financial sector: energy sector (Ringer *et al.*, 2007), fishery harvesting decisions (Alvarez *et al.*, 2017; Sanchirico *et al.*, 2008), biodiversity conservation (Figge, 2004; Koellner and Schmitz, 2006; Hoekstra, 2012), forest management (Matthies *et al.*, 2015; Knoke *et al.*, 2005; Knoke, 2008), agriculture (Castro *et al.*, 2015; Niggol Seo, 2010), water resource management (Marinoni *et al.*, 2011), invasive pest and disease surveillance (Yemshanov *et al.*, 2014), spatial planning (Hills *et al.*, 2009; Halpern *et al.*, 2011) and natural resource conservation under climate uncertainty (Crowe and parker, 2008; Ando and Mallory, 2012; Mallory and Ando, 2014). Scientific research in ecology have also recognised an effect of the diversification, like in the portfolio management, in natural systems, by which communities with high diversity tend to produce more stable streams of ecosystem services (Alvarez *et al.*, 2017).

Due to the presence of a significant uncertainty connected to the climate change impacts and the difficulties in reducing them in the future, MPT can be particularly useful for the climate change decisions, giving the opportunity to guide public decision-makers in facing this exceptionally complex framework.

3. ESSENTIAL MILESTONES OF THE MODERN PORTFOLIO THEORY

Although MPT is fundamentally based on the economic principles of the Cost Benefit Analysis and on the economic efficiency criteria, it makes use of a phenomenon which is observed in the formation of stock portfolios: returns are additive, while risks partially cancel each other out (Markowitz 1952, 1956). MPT leads to the identification of portfolios of measures and it gives the opportunity to identify investment solutions that are recommended to the decision-makers for their adaptation objectives. These portfolios are selected on the basis of two main decision criteria: i) the economic return of the investment (usually, the Expected Net Present Value); ii) the risk connected to the investment (usually represented by the variance or standard deviation of the economic return along the various possible futures). Even though these are the two key decision rules of the portfolio analysis, the selection of the preferred investment solution could then be helped by other criteria, such as the social values and preferences assessed by stakeholder engagements, as well as wider economic effects on – for example – employment.

In this section, the methodology of the portfolio analysis is briefly described, and the key terminology and the fundamental milestones presented.

3.1. Identification of portfolio manager and assets selection

In MPT the investment decisions are structured in assets, which can be collected in various portfolios. «Assets» are usually considered securities whose value is generated from a future flow of costs and benefits. The economic return of each asset is usually called the «asset's return». A «risky asset» is an investment for which the future return is uncertain. The deciding agent, called the «portfolio manager», wants to maximise the trade-off between economic return and risk, possibly choosing the more remunerative portfolio with the lower level of risk.

MPT was initially applied in the finance sector, thus considering stocks and bonds as risky assets and portfolios as an investment with a mix of various shares of these assets. However, this tool can also be applied to other frameworks. For example, in the agriculture sector the portfolio manager will probably be the farmer and the assets might be different variety of crops or different possible land uses; whereas in the energy sector the portfolio manager, as a public government decision-maker, has to decide among various mix of alternative sources of energy available, i.e. renewable or fossil.

Thus, the first step of the portfolio analysis requires two connected tasks: i) the identification of the portfolio manager, analysing her/his targets, values and preferences; ii) the definition of the assets available to the portfolio manager. The choice of the asset is a demanding duty, since the characteristics of the securities are essential in reaching the main goal of the portfolio analysis, i.e. the reduction of the risk connected to the investment. An effective portfolio is indeed more than a list of various good stocks and bonds (Markowitz, 1991). The performance of the portfolio strictly depends on the mix of the assets considered, which have to be accurately chosen, considering the relationships between them.

Although the capacity to generate revenues is essential for a good asset, another key principle in the selection among the different options is indeed the correlation between their performances. The correlation coefficient measures how two investments vary according to the different possible futures and it spans between 1 and -1, where 1 is the perfect correlation, 0 represents an uncorrelation and -1 a perfect negative correlation. If the securities vary in the same direction and with the same proportion, the correlation between them is perfect, whereas if they vary in the opposite way, at the same proportion, they will be negatively correlated. Portfolio diversification is effective when it regards assets which are less correlated or negatively correlated, whereas when the correlation is perfect and the assets proportionally vary in the same direction, the diversification has no effects and the risk is not reduced in the portfolio. Usually securities are correlated but not perfectly correlated and therefore diversification is generally effective in reducing the risk of the investment (Markowitz, 1991).

3.2. Estimating the economic performances of the assets selected

Once the assets have been identified, their actual and expected returns should be measured. The standard literature on MPT is basically focused on financial assets and therefore considers simple market prices and their future flows, finding a discount rate to actualise the future performances to the present. However, in recent years the use of MPT has been expanded to several other fields including land use choices and biodiversity preservation (Figge, 2004). These involve the management of public goods, thus complicating the evaluation of the benefits and costs of the measures. In some cases, indeed, benefits from natural resource management cannot easily be quantified in monetary terms, so the portfolio manager is obliged to use an alternative metric that can allow comparison of benefits (Alvarez *et al.*, 2017). As long as such a metric exists, it is possible for the MPT to be performed[3].

Following the traditional economic terminology of the Cost-Benefit Analysis framework, MPT requires the calculus of the Expected Net Present Value (ENPV) of each asset, i.e. the forecasted economic return of the investment on each asset, considering the revenues in a plurality of possible futures. Probabilities are usually assigned considering the past trends of the returns of the asset and developing a future pattern in some way related to these trends (Fabozzi, 2008). However, considering the context of climate change related decisions, the definition of probabilities about the future scenarios represents a problematic aspect of the analysis. Indeed, scientific knowledge is still insufficient for assigning likelihood to each climate change scenario. Indeed, even if the scientific community accomplishes a refined and complete understanding about the functioning of the climate system and its connection to the local environments, an uncertainty about the future pattern of the greenhouse gas emissions will remain. The information learnt from historical data might indeed lead to fallacies in beliefs about alternative futures, leading to a wrong set of probabilities for each possible scenario. This is why expert personal judgments are accepted in estimating the performance of the asset classes depending on their own understanding of the factors that influence the returns on asset (the political stability, the monetary and fiscal policies, the business cycles of sectors) and what their impacts might be (Fabozzi *et al.*, 2002).

However, according to Markowitz (1952) the ENPV is not enough for the identification of the best assets. The analysis of the risk connected to the investment is the other essential step in the MPT framework and it relies on the statistical concept of variance. This measure represents the dispersion or variability of the possible outcomes around the expected value. In the case of the finance sector, variance might show the range of the possible returns of a bond or a portfolio of securities around the mean value according to different possible future economic scenarios. When the

[3] In the review of Matthies *et al* (2019), they find that assets, and thereby expected returns, can be defined by some or all of the following key return components: i) access/ownership to the resource base/asset (e.g. land) i.e. where managed access is an indicator of effective biodiversity conservation; ii) biological growth component (i.e. periodic growth increment); iii) growth in the unit value of the output of the asset (i.e. transition between timber assortments); and iv) changes in total value (monetary or non-monetary) associated with the asset.

variance is 0, the investment is riskless and its outcome has no variability in the different possible future, although this situation is obviously uncommon.

Another means of representing the variability of the revenues is the standard deviation. The unit of measure of the standard deviation is the same (the variance is a square unit) and it might simplify the comprehension and discussion of the results of the analysis. Obviously, the greater the variance and the standard deviation, the bigger the risk of the investment (Markowitz, 1952; Fabozzi, 2008).

Considering a combination of two assets, the calculus of the variance is more complex, and it also depends upon the relationship between the assets. The information needed is the degree to which the economic performance of the two assets change together according to the different possible futures. In statistical terms, this is the covariance. The correlation might also be used, as it is similar to the covariance and it is estimated dividing the covariance of two assets by the product of their standard deviations. The correlation coefficient is a standardized number and it is comparable across different assets. It varies between +1.0, which represents the perfect co-movement in the same direction, and -1.0, the perfect co-movement in the opposite direction. If the correlation is 0, it means that the economic performances of the assets are uncorrelated. Thus, in the adaptation context, a value close to zero would suggest that the measures being introduced are effective over different parts of the climate risk uncertainly range.

Markowitz explains his approach to diversification as follows (Markowitz, 1952):

> *Not only does portfolio analysis imply diversification, it implies the «right kind» of diversification for the «right reason». The adequacy of diversification is not thought by investors to depend on the number of different securities held. A portfolio with sixty different railway securities, for example, would not be as well diversified as the same size portfolio with some railroad, some public utility, mining, various sorts of manufacturing, etc. The reason is that it is generally more likely for firms within the same industry to do poorly at the same time than for firms in dissimilar industries. Similarly, in trying to make variance [of returns] small it is not enough to invest in many securities. It is necessary to avoid investing in securities with high covariances [or correlations] among themselves.*

Thus, the assets with good economic return, low variance and which have the economic performances not perfectly correlated are the ones to be selected for the portfolio analysis. In the climate change context, the assets should ideally be specialised to be effective in different scenarios: i.e. some of the adaptation policies should be perfectly suited for a no/low climate change scenario, whereas other adaptation policies should be suited for scenarios with severe climate changes (Crowe and Parker, 2008). Thanks to this diversification, the portfolio can be effective in reducing the risk of investing all the resources available in just one adaptation policy perfectly suited for just one possible future.

3.3. **The aggregation of the assets in portfolios and the evaluation of their performances**

The following step of the MPT methodology is the aggregation of the selected assets in portfolios. Portfolios are made up by different shares of the available assets. As well as for the single assets, when the portfolios have been identified, their expected return (or expected net present value) and variance have to be estimated. Portfolios are usually made up by a plurality of assets and the variance must include the co-variance between each couple of assets which composes the portfolio. The standard deviation (and the variance) of a portfolio basically depends indeed on three key dimensions (Markowitz, 1991):

i) the standard deviation of each asset
ii) the correlation between each asset
iii) the amount of the investment assigned to each asset

Assuming the same value of standard deviation and the same amount of investment assigned to the securities, the correlation between the options is the essential value which determines the effectiveness of diversification in reducing the risk of the investment.

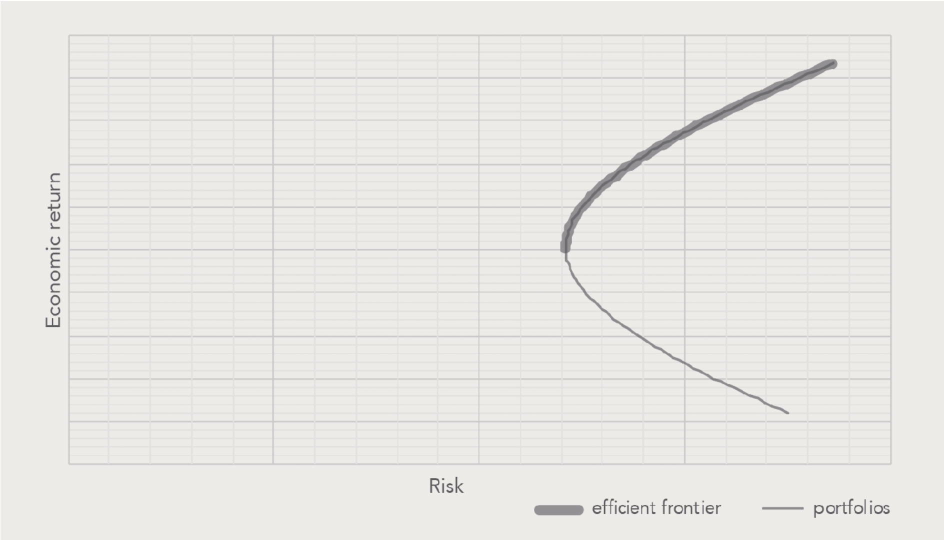
The mix of different assets in portfolios can thus reduce the risk connected to a single asset investment. However, there is a difference between systematic risk and unsystematic risk (Figge, 2004). The first refers to risk that equally affects all the assets of a portfolio, such as a drought for various crop plants (even if some plants are more robust to the lack of water than others). Diversification is thus ineffective on this kind of risk. The latter is instead the risk that affects the assets in different ways. A particular pest or disease can hit some crops whereas other ones could be immune. Therefore, diversification of crops in portfolios can have good effects on the reduction of the risk of disease.

3.4. **The efficient frontier**

When the economic return (or the ENPV) of the portfolios and the variances of these returns have been estimated, the last two steps of the MPT regard the presentation of the results on a diagram and the selection of the optimal portfolios. MPT calls «feasible portfolio» to every portfolio that an investor can construct given the assets available. The results can be showed on a graph, having on the x-axis the values of the variance (or standard deviation) and on the y-axis the economic returns. Considering a portfolio with just two assets, all the results will fall on a line, whereas if the portfolios combine three or more assets, the portfolios will cover an area on the graph.

In Figure 1 the portfolios made by the combination of two hypothetical adaptation measures is represented. The upper and lower extremes of the curve are the two adaptation options, whereas the curve represents all the feasible portfolios originated by the combination among the two assets. The thicker part of the curve is the efficient frontier, which starts in the point with the lowest standard deviation. All the investment solutions on the efficient frontier should be recommended to the decision-maker.

Figure 1. **THE EFFICIENT FRONTIER**



Source: Personal elaboration.

The efficient frontier can be considered an effective representation of the investment solutions available. Both in a private investment context or in a public decision environment, this figure could easily show the characteristics of the options available, effectively presenting the trade-off between revenues and risk.

3.5. **Portfolio selection**

The last step of the analysis is the choice of the optimal portfolio. Every portfolio on the efficient frontier can be considered an optimal solution. The choice depends indeed on the utility function of the investor, who also takes into account his risk attitude. If a person is faced with a decision, the alternative with the highest utility is the preferred choice. The investor's utility can be represented on an indifference curve, which collects all the combinations between economic return and risk which have the same utility for him. The grade of the curve is influenced by the attitude to risk of the investor. If the curve is more parallel with the horizontal axis, it means that she/he is risk seeking, because she/he is available to incur in a significantly higher risk of his investment even for a small increase in the economic return of his portfolio. Whereas, the more the line is vertical, the more the investor would have required a high economic return compensation for a little loss in the standard deviation. Thus, she/he is risk adverse (Boardman *et al.*, 2018).

4. PORTFOLIO ANALYSIS IN PRACTICE

The power of diversification has been widely recognized by the financial literature. However, the management of risk in an uncertain context is not just an issue of the financial market. Design of environmental, including climate change-related, policies are hampered by uncertainty, due to the presence of several unknown variables, e.g. the evolution of future climate conditions, the pattern of future human settlements, and the scientific uncertainty regarding the interaction of species. Consequently, some elements of portfolio analysis developed in the financial sector have entered in the scientific context of environmental management, with the aim of introducing interventions that are effective as well as robust to uncertainties. Recent experience is reported in the following paragraphs.

The strengths of portfolio analysis have been recognized in natural resource management and biodiversity conservation choices and in land-use decisions: it provides a means of aiding natural resource managers in their decision making by weighting returns and risks of different strategies to find the actions that optimize the provision of ecosystem service flows (Alvarez *et al.*, 2017).

A first interesting contribution of MPT to the biodiversity sector is proposed by Figge (2004). He presents the problem of the biodiversity conservation in a context where the choices of a decision-maker are constrained by a limited budget and the knowledge about the future outcomes is scarce. Figge (2004) designs a comparison between the portfolio management approach and the biodiversity conservation issue. Biodiversity is fundamentally similar to the portfolio creation, where the aggregation of different assets gives the opportunity to reduce the risk of return, not reducing the expected return of the investment. If we consider pharmaceutical purposes, the conservation of a plurality of plants could permit to preserve species that are useful for the discovery of new medicine. Figge (2004) makes a comparison between the portfolio manager and the biodiversity manager, which analogously tries to design a portfolio with an optimised risk-return ratio by optimising the mix of species, genes or ecosystems in the portfolio. Biodiversity is encouraged when there are various species mixed together, but it is determined not just by the quantity of species, genes or ecosystems, but also by the degree of diversity inside the community. The return of the biodiversity portfolio can be measured in other terms, not only using economic metrics. The expected agricultural yields could be expressed in physical terms and the return from bio-prospecting could be measured in numbers of new pharmaceutical active substances (Figge, 2004). Figge (2004) states that mixing two perfectly correlated assets will have no positive effects on the variance of the portfolio. Anyway, although some assets might be positively correlated (as the crops yields to average temperature and precipitations), they are seldomly perfectly correlated and the diversification effort is often effective. For example, the crops yields can increase or decrease depending on the climate variables, but different variety of plants have different ecological functioning and different sensitivity to temperature and precipitations. Thus, the portfolio manager has to consider the relations between the assets and their relative weights inside the portfolio.

The performance of one asset does not, though, necessarily affect the performance of another asset of the portfolio. The species of an ecosystem are instead symbiotic; therefore, the performances of an organism have effects on the other ones in the ecosystem. Another difference from MPT in the financial sector regards the irreversibility of the decisions in the biodiversity management, where non preserving a species might lead to the extinction of that species, compromising future investments on that asset (whereas the investment in the financial market can be usually changed year by year).

Koellner and Schmitz (2006) present the concept of biodiversity as an issue of portfolio management, showing that the increased level of biodiversity can improve the yield-to-variance ratio and increase the marginal benefit of adding biodiversity to a portfolio. Yield refers not only to direct financial performance, but also to any type of service provided by ecosystems (e.g. biomass production in agriculture and forestry, carbon dioxide sequestration, flood mitigation). Risk refers to the unpredictability of future yields and is determined by the variance in space and time. Systems with many species can buffer the disturbance better than systems with fewer species, because the probability is greater that some species will be able to maintain certain level of ecosystem services, even though others may fail to function. The paper shows how the improved biodiversity can have a powerful effect in achieving better mean-variance performances. However, they point out how portfolio analysis requires a rich amount of data, starting from a deep understanding of the mean level of an ecosystem service but also its variability in time and space.

MPT has also been employed in other natural resource management fields. Some authors used the portfolio analysis in the *fishery sector*, in the attempt to find harvesting strategies that increase the revenues while reducing the variability of the catchments. Sylvia *et al.* (2003) develop optimal portfolio frontiers for the pacific whiting fishery using three alternative benefit functions representing the objectives of different interest groups (seafood brokers, seafood processors, resource managers). The analysis generates risk return frontiers for all of them, considering different mixes of fish harvested. They compare the actual mix of species caught with the optimal portfolio efficient frontier for each actor and they find that the actual portfolio is sub-optimal for every point of view considered. They state: «*a portfolio approach provides industry and resource managers with a potentially valuable framework to evaluate complex natural resources issues and develop management strategies best suited to balancing multiple objectives*».

Edwards *et al.* (2004) consider again the fishery sector, in the attempt to find more robust management strategies to the plausible expected futures. The predominant approach the governments use to regulate harvests of fish and invertebrate resources treats species in isolation from each other, the so called single-species approach. This approach, based on the maximum sustainable yield (MSY) for each species separately, has been criticised by the scientific literature (Punt and Smith, 2001)). Therefore, they recommend a portfolio approach as a conceptual model to optimally combine stocks of wild fish species that ecologically interact when jointly caught. A similar aim has been settled in the analysis made by Sanchirico *et al.* (2008). The goal of their work is the use of the portfolio theory in setting catchments level for fishery. They demonstrate that this strategy can improve the yield while diminishing the variance of the fish available. The urgency of this new approach comes from the collapse of some fish stocks in the previous years. They considered the Ecosystem-based fishery management (EBFM) which requires recognition of system component interactions in determining management targets. Thus, they define an efficient frontier with different mixes of total available catches (TACs) for each species, considering the natural relations among them.

Further, MPT has been used for decisions regarding to investments in the *forest sector*. Knoke *et al.* (2005) develop a portfolio analysis with the aim to identify the better share of different tree species looking at their economic performance and its variability. Historically, in this sector, classical economic calculus leads to a superiority of the profitability of single species coniferous forest management. However, Knoke *et al.* (2005) state that this strategy conducts to an increase of the vulnerability of the forests and a variability of the revenues, due to the loss of biodiversity and a severe reduction in the resistance against storm, snow, ice, drought and insects damage of the forest stands. Moreover, growing trees is an extremely long-term investment in central Europe. Production times of 100 years and more are common and during its lifetime there are several risks that can considerably reduce the expected yields. This is why an investment in this field should be carefully planned, considering also that making changes to the investment during the lifetime of the forest is quite complex and, thus, the robustness of the initial decision is crucial. They consider the work of a Bavarian silviculturalist, Karl Gayer, who claimed, in the 1886, that the forest condition must be able to deal with the uncertainty of future development and recommended the use of «mixed forest». Starting from this theory, they use a portfolio analysis to compare the performances of a mixed forest management with single species forest management. They demonstrate that mixed forests decrease the risk, even if also the profitability of the forests fall. Risk adverse decision-maker can choose this kind of forest management strategy, due to a significant risk attenuation. They find that the mix between the spruce and beech investments can lead to a less risky strategy (the lowest variability is with 20% spruce and 80% beech). Knoke (2008) come back on this issue in another article with the aim to present different possible decision criteria for the assessment of the portfolios. He discusses three possible decision rules: i) the mean/variance; ii) the stochastic dominance criterion; iii) the information gap approach. He finds that these different decision rules have different data requirements and therefore they can be used accordingly to the information available. These topics have been discussed also by other contributions: Knoke *et al.* (2015) and Hildebrandt and Knoke (2009; 2011).

Another interesting perspective comes from Castro *et al.* (2015), who use portfolio analysis in the *agricultural sector* in an attempt to find the right balance between organic and conventional banana in Ecuador, using the organic one in reducing the volatility of the investments made. The organic cultivation is described as more costly due to more labour contained in the process, but it doesn't necessitate fertilizers and pesticides, thus, finally, the overall cost results similar. The conventional production is more productive but it is also more volatile, due to the general impoverishment of the soil, the losses of biodiversity and the contamination of the water resources. Moreover, consumers are willing to pay more for the organic products and the prices for these goods are usually more stable, as emerges from an analysis of historic data. Therefore, there is an interesting relationship among the two different production alternatives, suggesting the possibilities to explore the portfolio analysis methodology in the attempt to identify the opportunities made by mixing the organic and traditional production. In summary, although organic banana appears less attractive as a single option, this option, when embedded in a land-use portfolio together with other crops, may improve the economic return of the Ecuadorian banana farms (Castro *et al.*, 2015). Conclusively, they suggest the general importance of diversification in the management of a farm, even if with wealthier farmers, the attitude toward risk increases. «More intensive diversification is probably more important for poorer farmers, who are both more exposed to and more adverse to risk, and they usually lack strategies to hedge against risks. Ultimately, wealthier farmers can afford better technologies and have better access to information» (Castro *et al.,* 2015).

More specific experience in the *climate change* field is limited to few examples, focused on the biodiversity management and land-use allocation contexts. Ando and Mallory (2012) apply the MPT to optimal spatial targeting of conservation activity, using wetland habitat conservation in the Prairie Pothole Region (PPR). The entity responsible for the management of the protected area is the Fish and Wildlife Service and it seeks to quadruple the amount of habitat protected in the PPR. Lands have a different performance in the Cover-Cicle Index (CCI), a measure of wetland habitat quality which creates an order of land with different conservation priorities. The authors identify three different sub-regions of this reserved area in the North of the United States: Western, Central and Eastern. Under historic conditions, modellers find that the best wetland habitat is in the Central subregion and therefore the conservation efforts should be concentrated mainly on this site. However, the quality of the natural environment in that lands is highly influenced by the mean temperature and the distribution of the precipitations. Thus, climate change considerably changes the quality of these areas, eventually compromising the initial investment choices made. In the attempt to find a more robust investment solution to the different possible futures, they structure a portfolio analysis considering the design of different portfolios with different shares of the amount of land in each of the three parts available. The climate change scenarios considered are four (no climate change, +2°, +4° and + 4° C with precipitation increased by +10%) and they test two different distribution of probabilities for these futures. Due to the high uncertainty connected to climate change, they consider two sample probabilities distributions to demonstrate the sensitivity of optimal portfolio analysis to assumptions about outcome probabilities: the first distribution is called «no change likely» and is weighted heavily toward historic conditions, whereas the other is called «uniform» and assumes that each climate scenario is equally likely to occur. They consider as costs the value of the lands that must be purchased and as benefits the suitability of the land due to the Cover-Cycle Index. They structure two different analysis one just focused on the benefits and another one considering a ratio between habitat quality and land cost.

Four main conditions are identified for an effective use of the MPT: i) climate change raises a considerable uncertainty in the benefits and costs of a resource management policies; ii) adaptation decisions have to be made much time before this uncertainty might be resolved; iii) the policy is focused on a spatial region over which the outcome of interest is somewhat fungible; iv) although the MPT can be used in vary circumstances, the best results of the diversification exercise emerge when the performances of the different assets are negatively correlated.

Mallory and Ando (2014) presented another work on this case study, developing some key dimensions connected to the counting of the economic benefits of the preserved lands. They suggest using the economic value of the land in the case that economic value is not perfectly correlated with the parameter which measure the quality of the land. To generate plausible monetary values for the benefits associated with conservation of habitat which varies in quality, they use estimates of willingness to pay for wetland retention and restoration from a study in a Canadian portion of the PPR that borders the US. The analysis also makes assumptions about the possible evolution of the benefits according to the impacts of climate change. However, both the cost of the land and the willingness to pay could vary according to climate change and the scarcity of the land in the future and these values are essential in finding the correct shape of the efficient frontier. Therefore, an accurate analysis of these parameters is highly recommended.

Ando *et al.*. (2018) work again on the MPT in the natural conservancy context and they make a comparison between three portfolio analysis case studies in the United States, with the aim to find key characteristics which are good indicators of the suitability of the portfolio analysis: many negative correlations among the ecological returns in different assets; a second-best asset that has expected ecological returns almost as good as the returns in the best asset; and many assets that have little uncertainty in their ecological outcomes across climate scenarios. Those three characteristics are intuitive, so resource-investment planners can anticipate whether a case is likely to have any of those features and thus whether MPT is likely to have any of those features and thus whether MPT is likely to provide low-cost environmental risk reduction.

Another climate change case study is proposed by Crowe and Parker (2008), who show how MPT can use the results of a climate change impact model to select an optimal set of seed sources to be used in regenerating forests of white spruce in an environment of multiple, equally plausible future climates. This study shows that components of solutions are not selected to perform equally well across all plausible futures; but rather, that components are selected to specialise in particular climate scenarios. The negative correlation between the performances of the assets in the portfolios makes the investment more stable. Here, MPT is again recognized as a powerful instrument in dealing with uncertainty, helpful in taking robust decisions.

Dittrich *et al.* (2016) present instead an analysis of the adaptation strategies suggested for the livestock sector, and they recommend the portfolio analysis for the economic appraisal of long-lifetime measures in the attempt to combat heat stress in livestock. Their approach to address heat stress in livestock is to diversify the breeds in a particular herd to reduce the risk of heat stress while trading off some productivity. Having a number of high-productivity animals in the herd with low heat tolerance levels and a number of lower-productivity animals with high heat tolerance will achieve this objective. It should be noted that this is not an adaptation to long-term temperature changes (as the productive lifetime of a dairy cow usually does not exceed 5 years); rather, it is an adaptation to increased variability in climate due to climate change.

Another interesting analysis comes from the paper written by Niggol Seo (2010), which tries to evaluate the resilience to climate change of an integrated farm (crops and livestock) and a specialised farm on crop production. He believes that Africa farmers will adapt to climate change by moving away from a specialised portfolio in crops to a mixed portfolio and that the integrated farm will perform better in a hotter world. He considers the expected effects of an increase of the temperature and of the rainfalls due to climate change scenarios. He finds that climate change will have a negative impact on the agricultural sector in developing countries, affecting the revenues of both crops and livestock. Furthermore, He finds that specialised crop farms are more vulnerable to the climate change effects than the integrated ones due to portfolio diversification. In a similar work, Niggol Seo (2010) replicates the methodology used in the previous work, this time focusing on the South American countries, reaching similar results.

5. **CONCLUSIONS**

The Modern Portfolio Theory is fundamentally based on the seminal work of Markowitz (1952), which started systematising key concepts of the analytical approach, applying this methodology in the finance sector. MPT has the capacity to help decision-makers, both private and public, in planning investment in an uncertain framework, giving them the opportunity to find ways to reduce the variability of the expected outcomes, without compromising economic returns. As a consequence, MPT overcame the boundaries of the finance sector and it has been widely used in other fields, including energy sector, fishes harvesting decisions, biodiversity conservation, forest management, agriculture, water resource management, invasive pest and disease surveillance, spatial planning and conservation under climate uncertainty.

On the basis of our literature review, we identify that the MPT has various important strengths:

i) It is a strong analytical tool for the inclusion of the uncertainty and of a plurality of possible scenarios in the economic analysis; therefore, even though the climate change uncertainty is deep and it can significantly hamper the decision-making processes, there are strategies to take informed adaptation policies, robust to a high variety of possible climatic futures
ii) It demonstrates the power of diversification for the reduction of risk and for the increasing of the performances of a natural site or a natural resource
iii) It can be used in different contexts, due to its versatility and its capacity to deal with different kinds of data and measurements;
iv) The results are presented on the efficient frontier, an effective instrument for the communication of the performances of the different investments, collected in the various portfolios. The efficient frontier could be useful in various contexts in the attempt to show the available options and the risk connected to these solutions. Both technical and non-technical actors could be informed through this representation of the economic results of the analysis, effectively communicating the climate change effects on the policy outcomes.
v) It introduces new decision criteria besides the traditional economic return proposed by the cost-benefit analysis.

However, some limits also emerged:

i) In some cases, portfolio analysis requires a significant amount of data and information;
ii) Natural performances and service provided could be used instead of economic values in the attempt to extend the number of interventions that this tool can evaluate. However, in some cases the use of economic data leads to different results. Therefore, portfolio analysis seems to remain in the boundaries of an economic analysis, with the strengths and weaknesses of this field. It should be integrated with other inquiries: e.g. an analysis of the preferences of the local stakeholders, an extended analysis of the environmental or social effects of the project;
iii) Portfolio analysis still relies on probabilities for the evaluation of the ENPV;
iv) It requires good computational skills, a plurality of competencies and it is highly time consuming;
v) This instrument is not sufficient for the identification of the recommended measures for a specific community. Good policy processes should be designed, in the attempt to iteratively monitor and evaluate the performances of the measure, progressively updating the climate change scientific knowledge. Furthermore, a stakeholder engagement is essential, with the aim of designing more

comprehensive adaptation strategies, recognizing the values and the priorities of the local communities. Portfolio analysis is just a part of this wider process.

Thus, whilst the principles of MPT and its applications outside of the financial sector demonstrate its potential as an analytical tool with which to effectively handle uncertainties relating to climate change adaptation, the identified limitations need to be addressed to encourage its wider take-up. One promising direction, identified by Watkiss *et al.*. (2015), is to investigate the potential for the method's specification to be simplified without sacrificing its' analytical qualities. This 'light touch' approach might involve a broader brush approach to data collection related to the costs and benefits, perhaps using more aggregated measures of the various components that comprise the costs and benefits of adaptation investments. This might become feasible, for example, as the market for climate services, including climate scenarios, develops further and climate data providers become better able to tailor data provision to the user communities. More fundamentally, there is a need for those with experience in MPT application to better share the lessons that they have learnt and demonstrate the central principles involved in its' use.

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