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Bio-folio: applying portfolio theory to biodiversity

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Abstract. Genes, species and ecosystems are often considered to be assets. The need to ensure a sufficient diversity of this asset is being increasingly recognised today. Asset managers in banks and insurance companies face a similar challenge. They are asked to manage the assets of their investors by constructing efficient portfolios. They deliberately make use of a phenomenon observed in the formation of portfolios: returns are additive, while risks diversify. This phenomenon and its implications are at the heart of portfolio theory. Portfolio theory, like few other economic theories, has dramatically transformed the practical work of banks and insurance companies. Before portfolio theory was developed about 50 years ago, asset managers were confronted with a situation similar to the situation the research on biodiversity faces today. While the need for diversification was generally accepted, a concept that linked risk and return on a portfolio level and showed the value of diversification was missing. Portfolio theory has closed this gap. This article first explains the fundamentals of portfolio theory and transfers it to biodiversity. A large part of this article is then dedicated to some of the implications portfolio theory has for the valuation and management of biodiversity. The last section introduces three development openings for further research.

Introduction

Loss of biodiversity is regarded today as one of the great unsolved environmental problems (e.g. Swanson 1991, p. 181). The decline in biodiversity as an ecological problem has attracted increased public interest in recent years. It is, however, surprising in connection with the decline in biodiversity that the economically oriented discussion of biodiversity in recent years focused mainly on the correct valuation of species and biodiversity (e.g. Dixon and Sherman 1991; Gowdy 1997; Gauthier 1998; Weikard 1998; Garrod and Willis 1999; Lerch 1999; Fromm 2000; Pearce and Barbier 2000). Whether a value can and should be put on biodiversity is at the same time controversially discussed (e.g. Pirscher 1997; Hampicke 1999).

In this context many authors attach only secondary importance to issues of diversity, despite the central notion of diversity in the concept of *biodiversity*, i.e. the diversity of species, genes or ecosystems, in valuation and management issues. This is regrettable, as it must be anticipated that the value of biodiversity is determined not just by the quantity of species, genes or ecosystems but by their degree of diversity as well. Put simply: biodiversity is more than just an aggregation of all species, genes or ecosystems. If no account is taken of the degree of diversity, there is a risk of incorrect decisions being taken.

The emergence of portfolio theory (Markowitz 1952, 1959) provided issues of the diversity of portfolios with a theoretical framework. Markowitz's analysis related to financial securities. The analysis has not just had a theoretical benefit there, but has also impacted the behaviour of asset managers such as banks and insurance companies in the practical situation.

Interestingly, the parallels between issues of diversification of securities and issues of natural diversity are generally not acknowledged. This is surprising, because the correlation between diversity and stability in ecology has long been discussed (cf. for example Goodman 1975; Cronk 1997; Fjeldså and Lovett 1997; Hobohm 2000) and there is considerable research on the contribution of biodiversity to the resilience of ecosystems (Holling 1973; Perrings 1998; Perrings and Stern 1998). Resilience of an ecosystem can be interpreted as the ability to absorb changes and disturbances before it changes from one state to another (Holling 1973). Both ecosystems that are more stable and ecosystems that are more resilient should be less exposed to risk. Those authors who recognise the risk-reducing effect and therefore the economic value of diversification sometimes even term this the portfolio effect and refer to the parallels with the economic sciences (e.g. Groombridge et al. 1992, p. 426; Swanson 1992; Perrings 1995, p. 862; Swanson and Goeschl 1998). They recognise that the risk can be reduced by combining various species in a portfolio (Myers 1980; Swanson 1992) and in some cases even that the variation in return from the elements in relation to each other is of particular significance (Groombridge et al. 1992, pp. 426–430).

However, the authors do not explicitly refer to portfolio *theory* for an explanation. This is regrettable for two reasons. Firstly, only portfolio theory explains the precise connection between return and risks of individual species and the return–risk ratio of portfolios. A higher number of species, genes or ecosystems does not always lead to a lower risk. Only portfolio theory shows whether additional elements in a portfolio also reduce the risk. Secondly, the findings of portfolio theory provide the basis for modern portfolio management, which is of fundamental significance to the professional management of securities today. If it is assumed that a decline in biodiversity is unavoidable, the ratio between return and risk must be managed efficiently. The conclusion that diversity has to be maximised (Swanson 1992) offers little assistance in this context. We can learn from portfolio theory that the right construction of a portfolio can reduce the risk for a given return. Preserving biodiversity is therefore not necessarily linked to renouncing returns. Portfolio theory, however, also shows that maximizing diversity will reduce returns. From a portfolio theory point of view maximising biodiversity will thus not be optimal from a societal point of view.

Biodiversity: a societal asset

Portfolio theory is usually applied to assets such as shares. Genes, species or ecosystems can also be considered assets (e.g. Pearce and Barbier 2000). An asset is a *stock* whose value is deduced from a *future flow of benefit* (e.g. Krüsselberg 1984,

p. 5; Schmidt and Terberger 1997, p. 48). In so far as genes, species or ecosystems, for example in the form of agricultural yields, as a supplier of natural remedies, but also for example as a tourist destination supply a benefit in the future, they qualify as assets (e.g. Smith 1996b).[1] Portfolio theory links the return and risk of individual assets, i.e. genes, species and ecosystems in our case, to the return and risk of a portfolio of those assets.

This article adopts an anthropocentric utilitarian point of view; the value of biodiversity is therefore derived from its benefit to man. There are a number of accounts of the methods of economic valuation (e.g. Pearce and Turner 1990; Organization for Economic Cooperation and Development 1992; Kopp and Smith 1993; Heywood and Watson 1995; Perrings 1995; Smith 1996a; Geisendorf et al. 1998; Nunes and van den Bergh 2001). Regardless of the method of valuation chosen, three aspects have an effect on the value of a species or of biodiversity.

If a value is to arise, *firstly* a benefit must be expected. If no benefit accrues, no value arises either. This benefit may consist of an agricultural yield but also, for example, the aesthetic benefit of a landscape. The value depends among other things on the level of the benefit. This benefit accrues in the future. A past benefit does not have any effect on present value. Two other aspects result from this.

The value depends *secondly* on the time preference of the users of the resource. It is generally assumed that people prefer consumption of a resource today over later consumption (e.g. Bernholz and Breyer 1993, p. 73). The later the benefit of a resource accrues, therefore, the lower its present value is. As the benefit does not accrue until the future, it is furthermore uncertain.

Value depends *thirdly* on people's attraction or aversion to risk. It is generally assumed in economics that people do not like taking risks. They are averse to risk and are therefore prepared to sacrifice part of the return for a decline in risk. If species, genes or ecosystems are treated as an asset, their value depends on *what return* is to be expected *when* and *at what risk*.

The economic sciences have long been concerned with the valuation and management of assets created by humans. In the context of securities, they differentiate two issues. Firstly the value of the asset is ascertained by valuation, for example *company or share valuation* (for an introduction to the various valuation techniques, cf. e.g. Damodaran 1996). Secondly, *portfolio management* is concerned with the question of the optimum composition of a portfolio of these assets (cf. for an introduction e.g. Garz et al. 2000; Grinold and Kahn 2000). This separation between valuation of assets and composition of portfolios is also reflected in the practice of asset management. Asset managers separate the functions of analysts from the functions of portfolio managers. Analysts estimate the value of securities. Portfolio managers decide which securities are considered in what

[1] For an overview of other flows of benefit, cf. for example Geisendorf et al. (1998, p. 160) or Myers (1980, p. 57). In describing the benefit of genes, species or ecosystems, this article generally refers to agricultural and pharmaceutical benefit. The reason for this is that this benefit is immediately understandable and undisputed. These observations are, however, in principle applicable to any flow of benefit which accrues in the future and cannot be predicted with certainty.

quantity in the portfolios. Investors assume that value can be created not just from a 'correct' valuation but from suitable composition of the portfolio as well. To summarise briefly, it is portfolio managers who decide on investments, not analysts.

Economic questions of biodiversity to date are mainly looked at from an *analyst's perspective*. The issue of the value of species (e.g. Boman and Bostedt 1995; Simpson et al. 1996; Stevens et al. 1997; Artuso 1999) or of ecosystems (e.g. Dixon and Sherman 1991; Barbier 1994; Laughland et al. 1996) is to the fore. The decline in biodiversity is then, logically, attributed to species or ecosystems being incorrectly valued (Wood 1997) or to the value and costs of conserving the species or ecosystem falling apart (Perrings 1995, p. 829; Mason 1996; Swanson 1996, 1999, p. 307; Geisendorf et al. 1998, p. 170; Drucker et al. 2001). It is implicitly, or even explicitly, assumed that conservation is economically appropriate if the expected benefit exceeds the expected costs (e.g. Dixon and Sherman 1991; Pearce 1995).

The way in which *portfolio managers* view the situation, on the other hand, is usually not looked at. This is surprising, because it is specifically the task of a portfolio manager to diversify portfolios in an optimum manner. The task of a portfolio manager of biodiversity, by analogy, would be to construct a portfolio with an optimised risk–return ratio by optimising the mix of genes, species or ecosystems in the portfolio.

This article concentrates on the point of view of portfolio managers. Portfolios in this article are collections of genes, species or ecosystems. We presuppose that the portfolio elements (e.g. species) have been valued or that there are at least assumptions on the return of the portfolio elements. It is not necessary that all existing species, genes or ecosystems have been valued. Portfolio theory can also be applied to a subset that has been valued. Furthermore, the return need not be valued in monetary terms. Expected agricultural yields could be measured in physical terms and the return from bio-prospecting could be measured in numbers of new pharmaceutical active substances.

The fact that biodiversity is valuable is of course not new. However, resources to protect biodiversity are scarce. The allocation of resources to protect biodiversity is thus a typical economic problem. A number of economists (e.g. Weitzman 1992, 1993; Solow et al. 1993; Weikard 1998, 2002; Mainwaring 2001; Polasky et al. 2001) have approached this problem by developing measures that allow to quantify the degree of biodiversity. They implicitly assume that the degree of biodiversity correlates with the value of biodiversity. Using a Cost–Benefit Analysis these measures would then allow to maximise biodiversity for a given budget.

Portfolio theory takes another approach. From a portfolio theory point of view, species, genes and ecosystems will or might provide a return in the future. This return is usually subject to risk, i.e. the return cannot be predicted with certainty. We can distinguish between two kinds of risk in this context. In some cases the existence of a future return is certain but the scale and/or the time of the return is uncertain. This is e.g. the case for agricultural yields. One can be quite sure that there will be a yield but one knows neither the exact amount nor the exact time of the harvest. In other cases even the existence of a future return is uncertain. This is typically the case for bio-prospecting returns: a species might not provide any return at all in the future. Portfolio theory can be applied in both cases. By combining genes, species or ecosystems in a portfolio some of this risk can be diversified away. Portfolio theory allows to compare the (expected) return of a portfolio of genes, species or ecosystems with the (expected) risk.

The cost–benefit approach taken in past research and the portfolio theory approach taken in this article are fundamentally different. Cost–benefit approaches allow to determine the maximum benefit attainable, i.e. the maximum degree of biodiversity, with a given budget. In the logic of these approaches there is thus always a trade-off between the money that is spent on the preservation of biodiversity and the degree of biodiversity. Preserving biodiversity uses up resources. Cost–benefit analysis helps to spend those resources efficiently.

Portfolio theory aims to identify portfolios that offer more return for a given amount of risk or less risk for a given return. Since part of the risk can be diversified away, not-diversifying is irrational for risk-averse actors. Portfolio theory therefore focuses on the return that is lost by insufficient biodiversity. In economics, investors that do not diversify are usually considered to be irrational.

The subsequent section transfers the basic principles of portfolio theory to issues of biodiversity and in so doing lays the foundations for a portfolio theory of biodiversity. The next section considers the consequences which may result from a portfolio approach of this kind for the management of biodiversity. Some implications are presented which, in the management of stock portfolios, are already regarded as self-evident today and can be deduced from the key rule of portfolio theory: return is additive and risks partly cancel each other out.

Fundamental features of a portfolio theory of biodiversity

Return and risk are at the centre of portfolio theory. Portfolio theory and portfolio management make 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, 1959). This phenomenon allows portfolio managers to lower the risk of the complete portfolio without necessarily sacrificing return. As investors are generally regarded as averse to risk (e.g. Bodie et al. 1999, p. 148), from the point of view of the investor this leads to an improvement in portfolios, that is to say to a higher value.

These relationships are explained below by taking the example of a portfolio containing two elements (for similar treatments of stock portfolios see Elton and Gruber 1987; Bodie et al. 1999). Portfolio theory can be usefully applied to this portfolio, if the elements provide a future return and if this return is subject to risk.

Species, genes or ecosystems have an expected return. The return, in the anthropocentric utilitarian point of view adopted here, consists of the expected benefit which society derives from the species, genes or ecosystems. This includes, for example, the supply of food or use for tourism. This return is, however, uncertain, that it is to say attended by risk. This risk can be partially diversified by combining various species, genes or ecosystems in a portfolio (Groombridge et al. 1992, pp. 426–430; Swanson 1992, 1994; Heywood et al. 1995, p. 862).

The future yield of crop plants such as maize or soya is uncertain (e.g. Kaylen et al. 1992; Porter et al. 1998). A portfolio of crop plants can therefore be taken as an example of the effect of diversification.

Three items of information are required in order to describe the portfolio (cf. for financial portfolios e.g. Olson 1999, p. 83):

- What expected return and what expected risk does crop plant A have?
- What expected return and what expected risk does crop plant B have?
- What relationship exists between the variation in return of the two crop plants?

The question of the variation in return is of particular interest here. Three typical variations in return can be distinguished. The elements may firstly vary in a *parallel* manner. Whenever crop plant A provides more benefit, crop plant B provides more benefit too. The elements may, secondly, vary in an *opposed* manner. If crop plant A provides less benefit, crop plant B provides more benefit. The variation may also be *uncorrelated*, i.e. not show any relationship.

The relationship between the variation in return on the two elements is important, because it determines the risk of the complete portfolio. Elements whose variation in return is uncorrelated or even opposed are of particular interest to portfolio managers. In such cases the risks of the individual elements, i.e. the risks of the expected return of the crop plants, cancel each other out as a result of the decrease of the return of one crop plant being offset by the increase of the return of the other crop plant. Each element can be placed in a coordinate plane indicating its risk and return. Depending on the mix of the two elements the portfolio will have different risk–return characteristics. Line a in Figure 1 indicates risk and return of portfolios with a different mix of the two crop plants. The point where the portfolio is on line a depends on the weighting of the particular elements in the portfolio, i.e. the percentage a crop plant makes up of the portfolio. The risk can even be completely diversified away (point C on line a) by correctly weighting, i.e. by finding the right mix of crop plants A and B. In this case the decrease in return of one element is always offset by a corresponding increase in return of the other element.

This diversification effect does not come to bear, however, if the species follow a completely parallel variation. The portfolio in this case, depending on the particular weighting, is on line b. If crop plant A performs well, this is also true of crop plant B. Risks will not cancel each other out and can thus not be reduced by combining the elements in a portfolio. The risk of the portfolio will correspond to the weighted average of the individual risks.

Depending on the relationship between the returns of the elements contained in the portfolio, the characteristics of the portfolio differ more or less clearly from the characteristics of the individual elements. It is appropriate to assume that the variation in the yield of crop plant species as a rule is positively correlated (e.g. Groombridge et al. 1992, pp. 430–433; Lamadji et al. 1995). Good weather conditions, for example, will lead to high yields for crop plants. Adverse weather conditions, such as drought, lead to losses (Kaylen et al. 1992, p. 517; Naylor et al.

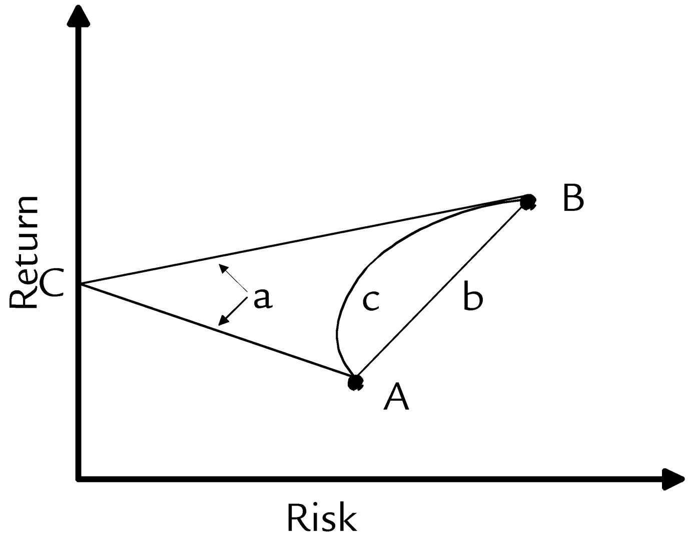

Figure 1. Relationship between return and risk for a crop plant portfolio (cf. similarly for stock portfolios; e.g. Elton and Gruber 1987, p. 44).

1997, p. 52). It is unlikely, however, that yields are perfectly correlated. Different organisms have differing ecological tolerances in relation to variable environmental factors (ecological valency) (e.g. Schäller 1991). While one crop plant, for example, can withstand drought, another proves its merit in wet weather conditions.

Neither a completely parallel (line b) nor a completely opposed (line a) variation in benefit will exist. Line c will therefore best describe the variation in benefit to be found in most cases of crop plant portfolios. The closer the portfolio is to point A (B), the higher the proportion of crop plant A (B) in the crop plant portfolio. The portfolio will be situated on point A (B) if the portfolio consists only of crop plant A (B). Whether the portfolio is situated on lines a, b or c depends on the correlation between the two crop plants.

An American study comparing the relationship between the variability of wheat yields and the size of the cultivated area shows that an agricultural portfolio effect of this type is more than a theoretical construct (Schurle 1996). All other things being equal, with a larger cultivated area the portfolio size should increase and the portfolio variability, i.e. the portfolio risk, fall. This portfolio effect can also be empirically observed.

Similar portfolio observations can also be made for example for future, tourist, aesthetic or pharmaceutical benefit. Here too the future benefit in general is uncertain and does not correlate or does not correlate completely.

Figure 2 therefore describes a typical shape of the yields of biodiversity portfolios. It resembles the pattern of line c in Figure 1. Where the portfolio is situated on the line between points A and B depends on the weight of the species or ecosystems, i.e. the fraction of the portfolio they represent, in the portfolio. The

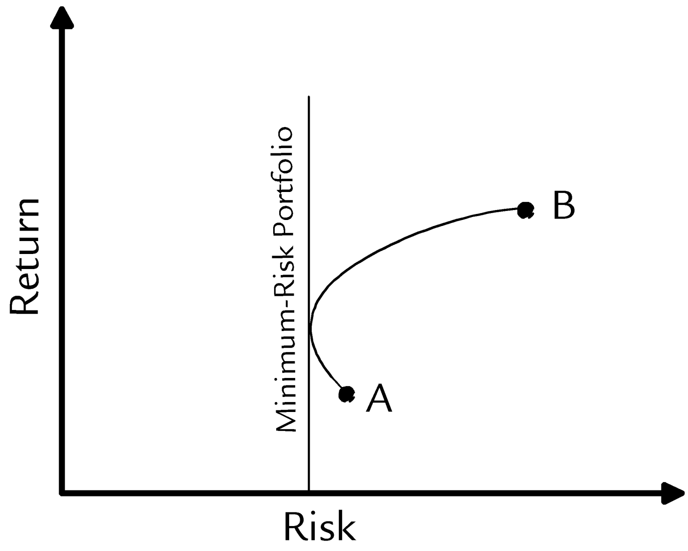

Figure 2. Return–risk relationship of a crop-plant portfolio.

higher the percentage of element A in the portfolio, the closer the portfolio will be to point A and the more the characteristics of the portfolio will resemble the characteristics of element A.

This illustration allows us to define the minimal-risk portfolio. It consists of both types of species or ecosystems and not just, as might be thought at first glance, the lower-risk type. Part of the risk can be diversified away by combining the types of species or ecosystems. The return of the portfolio lies above the return of the lower risk portfolio element at the same time.

This diversification effect can be further strengthened by considering other crop plants in the portfolio. Figure 3 shows a typical progression of a portfolio risk as a function of the number of elements such as genes, species or ecosystems considered. The more elements the portfolio has, the better risks can be diversified away: the portfolio risk falls. In general, however, it is not possible to diversify away the whole risk. The curve asymptotically approaches a level of risk which it does not pass below, even if the portfolio is enlarged.

An extreme drought, for example, can lead to a failed harvest. This non-diversifiable risk is also termed a *systematic risk*. All elements of the portfolio are exposed to that risk. The effect of a drought on the yield of a crop plant correlates with the effect of the drought on another crop plant. The diversifiable risk by analogy is termed an *unsystematic risk*. An unsystematic risk may consist for example of a pest infestation which only threatens some crop plants.

If such a large portfolio with more than two species is transferred to the risk–return representation chosen above, the picture illustrated in Figure 4 is obtained. The points in Figure 4 are placed according to the expected risk and return of the species they represent. The line that encompasses the portfolio elements represents

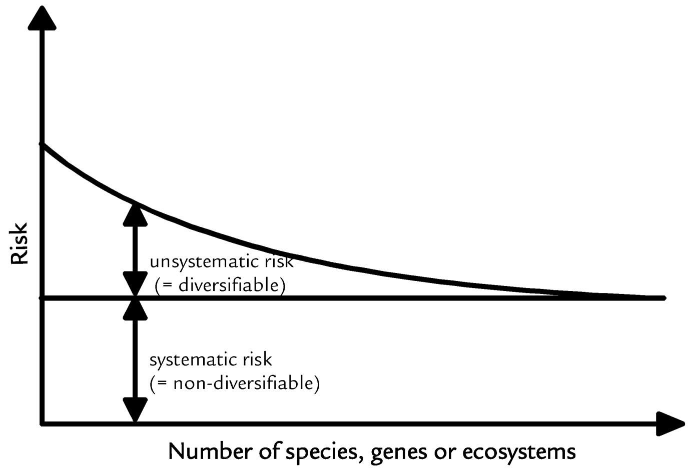

Figure 3. Reduction in risk by diversification.

the combination of portfolio elements that result in portfolios with the best risk–return characteristics. The portfolios that form this line are called efficient (Markowitz 1952, 1959). The line illustrates the most advantageous return–risk combinations which can be achieved by combining elements in a portfolio. There are no possible portfolios to the left of this line. If there was a portfolio to the left, it would be encompassed by the line. Portfolios to the right, i.e. within the area the line encompasses, are not efficient, since there are portfolios that offer more return for the same amount of risk.

As this illustration also shows, the risk can be diminished but not completely removed by diversification due to the existence of systematic risk. There is risk on a portfolio level as long as there is any variability of the portfolio return. A risk-free portfolio of this type would have to touch the return axis (y-axis).

These observations can be transferred analogously to other uses (e.g. future pharmaceutical use) of biodiversity, as long as the induced return is uncertain.[2]

As shown above, it is in principle possible and appropriate to transfer portfolio theory to biodiversity. Some important differences do, however, exist between biodiversity and securities portfolios.

Above all it is necessary on the one hand to point to the significance of symbioses in biodiversity. It can be assumed in the case of stock portfolios that the decision to invest in a stock does not have any effect on the return from a second stock. Investment in one stock is not causally linked to the success of a second stock. Organisms, by way of contrast, enter into symbiotic relationships. A symbiosis or symbiotic relationship is understood as meaning "[. . .] organisms of different species living together to their mutual advantage" (Vogel and Angermann 1990, p.

[2] Strictly speaking portfolio theory could also be applied when the return is certain. Portfolio theory would, however, not provide any additional insights in that case.

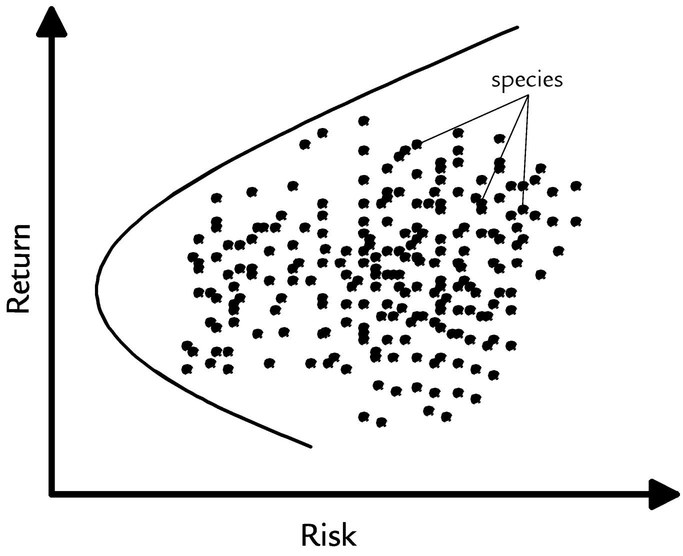

Figure 4. Return–risk relationship of a large portfolio.

247). If a close symbiotic relationship exists between two organisms, and if an organism is 'disinvested', the expected return from the second organism necessarily falls. This difference in comparison with stock portfolios additionally underlines the significance of forming portfolios. Symbioses can be explicitly taken into account by treating elements in a close symbiotic relationship with each other as a single element.

Investments and disinvestments in securities, on the other hand, are reversible. A share which is excluded from the portfolio one year can generally be considered in the portfolio again the following year. Exclusion from a biodiversity portfolio may, however, be final, that it is to say irreversible (e.g. Swanson 1992). If a species, for example, only occurs in one area and is not considered in the portfolio there, it will generally become extinct. It then cannot be considered in the portfolio again at a later time. Irreversibility should be taken into account in decisions on biodiversity. It does not, however, have any fundamental effect on the significance of portfolio considerations.

Implications

The preceding section has outlined the fundamental features of a portfolio theory of biodiversity. Biodiversity represents a natural portfolio of a large number of species, genes and ecosystems (e.g. Brown et al. 1993; Swanson 1997). Portfolio managers combine various elements (e.g. securities or crop plants) into a portfolio. In doing so, they make use of the fundamental finding of portfolio theory that returns are additive whereas risks diversify. They consequently do not look at the development of individual elements but at the development of the complete portfolio.

There has been discussion for many years in economics on how portfolios are to be put together (e.g. Sharpe 1970). It is of particular interest for the management of biodiversity that consequences for the management of biodiversity can be deduced from the practice of the management of stock portfolios. Some of these consequences will be formulated in this section. They become particularly clear in the example of agricultural use. Transfer to other types of use is possible by analogy.

Every decision must weigh return against risk: additional risk must be offset by additional return

Economic decision makers like return, but not risk. This is a fundamental assumption made by portfolio managers. It is also reflected in the behaviour of investors, who generally demand risk premiums to take on risks. As a result of this assumption, portfolio managers weigh return against risk. They are only prepared to take on an additional risk if they may also expect an additional return.

This aversion to risk must also be taken into account in valuing biodiversity. A risk in this case always exists when the future benefit cannot be precisely predicted. From an economic point of view, the future return of most species, genes or ecosystems is uncertain, that is to say it shows a risk. This applies regardless how it is ascertained or whether it is, for example, an expected aesthetic, pharmaceutical or agricultural return that is concerned. This risk is offset by the expected return. The higher the expected return, the more likely it is that the risk will be accepted.

The risk of genes, species and ecosystems can be partly diversified away

The future return of a species or ecosystem is not certain; a risk exists. In the case of a crop plant, this risk may, for example, consist in the yield being decimated by an epidemic. Portfolio managers combine many elements in a portfolio. The risks of individual crop plants in general partly cancel each other out, if they are combined in a portfolio (cf. the preceding section). Unsystematic risks can be diversified. They disappear on a portfolio level. Systematic risks cannot be diversified. They remain on a portfolio level. Risk-averse actors who can hold a well-diversified portfolio of genes, species or ecosystem must thus only be concerned about the systematic risk of the genes, species and ecosystems of their portfolio.

Large landowners, countries or continents, like investors, can form portfolios by growing various species. The larger the areas which can be cultivated, the easier this will prove to be for them. As already mentioned, a positive relationship of this kind between cultivated area and decline in risk can in fact also be observed (Schurle 1996). If the portfolio elements are exposed to unsystematic risk, this has the desired effect. It is rare for the whole portfolio to be affected by the risk. If the risk of the portfolio elements has primarily a systematic character, however, forming a portfolio does not provide a solution either.

This example can be extended in an analogous manner to other uses of biodiversity. Experience shows, for example, that the future pharmaceutical benefit of plant species is uncertain (Aylward 1995; Pearce and Puroshothaman 1995). Only a few of the different plant species will probably be put to medical use in the future. The future yield of a *particular plant species* may therefore be regarded as extremely uncertain. It is highly probable, on the other hand, that some plant species in the biodiversity portfolio will be used for medical purposes (cf. for a specific example Mendelsohn and Balick 1996). It may also be assumed that future medical use of the *complete set of plant species* can be predicted with greater certainty than the return of a particular plant species. The future medical benefit of all plant species is nevertheless uncertain. The diversification effect consequently does not allow the entire risk to be diversified away. The portfolio of plant species will show some risk.

Cost–benefit rules do not necessarily apply on a portfolio level

A simple cost–benefit decision-making rule is repeatedly cited in connection with decisions, including in relation to biodiversity (e.g. Marggraf and Birner 1998; Plän 1999). This states that an action or a project should be carried out if the expected return exceeds the expected cost (e.g. Organization for Economic Cooperation and Development 1992, p. 9). This relationship only applies simplistically, however, if either only one alternative can be implemented at the same time or no risk exists. If more than one alternative can be implemented at the same time, it is generally worthwhile forming a portfolio.[3]

If the simple cost–benefit rule applied, it can be imagined that the work of portfolio managers would be simple. The portfolio would consist of only one element, the element with the best cost–benefit ratio. A rational portfolio manager of biodiversity, however, also considers species which do not fulfil the cost–benefit decision-making rule, provided they contribute to diversification. This primarily relates to those very species or ecosystems whose returns have a low or even negative correlation with the returns of the other species or ecosystems in the biodiversity portfolio. This is, of course, an extremely complex task. As a rule of thumb, the lower the correlation with the other species or ecosystems in the biodiversity portfolio is, the lower the expected benefit of a species or ecosystem may be.

Portfolios of genes, species or ecosystems will always have a comparable or better return–risk ratio than any individual element of this portfolio

Portfolio managers combine elements in a portfolio to diversify risks, i.e. reduce them at the level of the complete portfolio. In this way portfolio managers build up portfolios with an interesting characteristic: the risk–return characteristics of the portfolio are more advantageous than the risk–return characteristics of any randomly chosen element or any randomly chosen combination of elements in the same

[3] It is specifically worthwhile when the risks are not correlated or are only incompletely correlated with each other.

portfolio. A portfolio of this kind offers more return per risk accepted than arbitrarily chosen elements in the portfolio.

This can be shown in Figure 5. The points stand for elements with different return–risk combinations. It corresponds to line c in Figure 1, which only took account of two elements. The line in Figure 5 reproduces the return–risk characteristics of various combinations of the elements of the portfolio. All the points which lie above point A on the line have a more attractive return–risk combination than individual elements. Point A simultaneously indicates the combination with the lowest risk which can be achieved with the elements.[4] Point B, for example, is of no interest. For the same risk, a higher return is achieved (point C) or it is even possible by skilfully combining the elements to create a portfolio which promises higher return at a lower risk (point A).

As a return–risk ratio superior to the return–risk characteristics of each individual element or any chosen subset of the portfolio can be achieved by combining several elements, portfolio managers generally include several elements at the same time, making sure that portfolios are well diversified.

The expected returns and risks of crop-plant species (e.g. maize, soya) have been repeatedly discussed (e.g. Nagi and Khehra 1996; Naylor et al. 1997). The risk in this case consists of a possible divergence from the expected return.

In principle, a species which in comparison with another species promises a

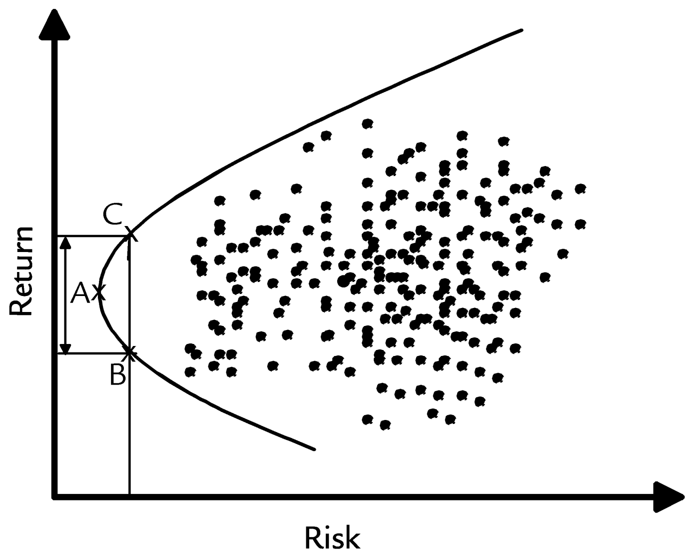

Figure 5. Return–risk characteristics of a large biodiversity portfolio.

[4] In financial portfolios a lower risk and portfolios with more attractive return–risk combinations could be achieved by considering a no-risk stock or by raising loans. This expansion is not examined here, as application to biodiversity does not appear appropriate (for these expansions, see Tobin 1958; Sharpe 1964).

higher return at a comparable risk or a comparable return at a lower risk is to be preferred. A combination of various species will nevertheless *in many cases* show a better return–risk ratio than a single species. If the portfolio includes this single species, a portfolio can *always* be constructed which shows at least an equivalent return–risk ratio. For this reason, an experienced portfolio manager, commissioned to put together a maize plant portfolio, would for example resist the temptation only to include one maize plant species, even if this promised particularly high returns at low risks.

Portfolios of genes, species and ecosystems with an attractive risk–return ratio will also consist of low-return genes, species and ecosystems

Most asset managers separate the valuation of shares and the construction of portfolios. Share analysts forecast the development of share prices and make buy and sell recommendations. However, portfolio managers take account of these recommendations. Portfolio managers often include shares that are considered unattractive by share analysts. The reason for this is in the differing perspective. Analysts issue an opinion on individual shares. Portfolio managers, on the other hand, have optimising the complete portfolio in mind, and a low-return stock may certainly have a place in a portfolio of this kind. The portfolio manager estimates the effect a block of shares has on the performance of the complete portfolio. Whether a stock has a place in a portfolio therefore depends on what other stocks are already in the portfolio. A share is the less important for a portfolio, the more it correlates with other shares in the portfolio. As a rule of thumb, the more shares with similar characteristics are already in the portfolio and the more unimportant a stock is, the easier it is to do without it.

A similar situation applies to biodiversity. Anyone who determines the value of a species or an ecosystem in isolation adopts the perspective of an analyst. However, the decision on which species it is easiest to do without must be taken from the point of view of the portfolio manager. The expected yield and the expected risk of the species is just one criterion. The portfolio manager optimises the return–risk characteristics of the complete portfolio and in so doing estimates the effect of inclusion or exclusion on the return and risk of the portfolio. It may be assumed that the risk of a biodiversity portfolio is lower the more different the species in the portfolio are. Doing without low-return species, on the other hand, leads to a homogenisation of the portfolio. As a result, both the return and the risk of the portfolio generally rise (Swanson 1992). The portfolio manager therefore has to weigh the degree of diversity and the return of the portfolio. In principle, however, a species which has a poor return–risk ratio but clearly differs from the other species may in certain circumstances be more valuable to the portfolio than a species which, although it has a better return–risk ratio, resembles the other species in the portfolio.

Portfolios of genes, species and ecosystems with a high return may point to high risks

Portfolio managers have to achieve the highest possible return for a given risk.

Problems can nevertheless be caused not just by portfolio performance which is too poor, but by portfolio performance which is too good as well. A very poor or a very good return with a well-diversified portfolio is rare, as low and high returns of the individual elements generally balance each other out.[5] Performance sharply above or below average may therefore be a sign that the portfolio manager has taken on a high risk due to inadequate diversification. It is a problem that a risk-induced above-average return of this kind may persist for several years (cf. analogously Figge 1998, 2001) and might erroneously be interpreted as a sign of low risk. If professional return analysis is not undertaken, a risk-induced above-average return of this kind may provide a false incentive.

Analogously sharply above-average returns on a biodiversity portfolio such as a crop-plant portfolio may be pointers to low biodiversity (e.g. genetic depletion). Greater uniformity of the returns of the individual species can be anticipated with low diversity. This represents both an opportunity (above-average returns) and a danger (below-average returns). With high diversity, on the other hand, smaller deviations from average returns are to be expected, as high and low returns of individual species offset each other. High returns in a case of this kind should therefore also be interpreted as a warning sign of a possibly high risk. Increased homogenisation of the portfolio should in any case only be adopted against an additional expected return. The fact that increasing risks due to homogenisation of biodiversity portfolios is not just a theoretical danger is shown by failed harvests, which are attributed to genetic depletion (cf. for an overview Groombridge et al. 1992, p. 428).

The return of genes, species and ecosystems whose risk can be diversified can be discounted using a risk free rate

Present-value methods have now largely become established for the valuation of shares and other securities. The present value of the expected inflows of funds is ascertained to calculate the value of a stock or other securities (e.g. Rappaport 1986; Brealey and Myers 1996, pp. 12–17; Damodaran 1996, pp. 219–234; Volkart 1998). The future inflows of funds are discounted for this purpose. The interest rate reflects firstly the time preference of the investors and secondly the risk taken. A no-risk rate of interest is therefore used to discount a flow of funds which can be predicted with certainty. If there is a risk, this rate is increased. The present value of future flows of funds consequently falls. Higher-risk stocks in this way have a lower value for the same expected returns than low-risk stocks. This reflects the aversion of investors to risk.

As portfolios cause the diversifiable, unsystematic risks to disappear, an investor therefore only has to bear the non-diversifiable, systematic risk. Only this risk therefore has to be taken into account in the discount rate. If the entire risk is diversifiable, the portfolio is devoid of risk. The expected inflows of funds in this

[5] In the case of a share portfolio, this can obviously be seen in comparison with a benchmark such as a share index. In this case high outperformance or underperformance, i.e. a wide divergence, in comparison with this benchmark is rare.

case can be discounted at the no-risk rate of interest, although each individual element is subject to a risk.

This also applies in an analogous manner to biodiversity portfolios and is of interest for example in the valuation of individual species for future pharmaceutical use. It is assumed that the future benefit of a species will have a lower value the more unlikely it is that this benefit can be tapped. A medicinal plant with known properties is attributed a higher value at the same expected return than a plant whose medicinal properties are not yet known. This is expressed in the application of a lower discount rate for the benefit of the known medicinal plant. This may be an incorrect valuation from the point of view of portfolio theory. The level of the discount rate depends on how subject to risk the portfolio of all medicinal plants is. The question is therefore with what probability is what benefit derived from the portfolio of all potential medicinal plants. The more certainly the benefit of the portfolio can be predicted, the lower the discount rate is for the use of the individual species whose individual benefit is uncertain. If the use of the complete portfolio is predictable with great accuracy, the same discount rate can be used for the expected benefit as for the benefit of the known medicinal plant.

Similar observations can also be made for the agricultural use of crop plants. Here too, a higher certainty of yield of a crop plant leads to a reduction in the discount rate and therefore to a higher value. As mentioned above, this only applies to a limited extent from the point of view of portfolio theory. If success is achieved in establishing a no-risk or low-risk portfolio of a crop plant by a suitable mixture of different species, a low discount rate can (also) be used for the portfolio of these species, although the yield of each individual species is uncertain.

It is not just the number of species, genes and ecosystems but their fraction of the portfolio (portfolio weight) that is of interest

As a rule of thumb, the more different elements are considered in a portfolio, the better the portfolio is diversified. The number of elements is, however, only one criterion of the quality of the diversification. Another criterion is the *weighting* of the elements, i.e. the fraction of the portfolio an element represents in the portfolio. A portfolio whose value is determined almost entirely by one element entails almost as much risk as this one element. Equal weighting of all elements is a way of obtaining a portfolio which is well diversified and therefore carries less risk. This type of equal weighting may, but need not be, appropriate. The characteristics of the portfolio, for example how much risk they entail, are altered by a change in the weighting of the elements.

In agricultural use, as high a number of different species of a crop plant as possible is desirable in principle. A portfolio of this kind is illustrated, for example, in Figure 6. The line illustrated there represents the possible efficient return–risk characteristics of the portfolio. In principle, the more crop plants the portfolio has, the closer it comes to the y-axis, the lower the risk is (cf. also Figure 2). Point A in Figure 6 can be reached with optimum, that is to say risk-minimising weighting. If the portfolio shows substantial overweighting of a species, however, the diversification is insufficient; the portfolio has an unnecessarily high risk. Point B, for example, represents the return–risk characteristics of a portfolio of this kind. Point C can be reached by expanding the portfolio and weighting accordingly. This point shows a lower risk at the same expected return.

In a crop-plant portfolio not only must a sufficient number of different crop plants exist, but they must also be weighted accordingly. The mere existence of a species in a portfolio is not sufficient.[6] Not just the number of species, genes and ecosystems but their weighting as well must therefore be considered in the management of biodiversity.

Complexity of the portfolio management problem can be reduced by class formation

A portfolio manager can resort to a virtually unlimited number of securities to build up his portfolio. In practice it is impossible to consider all possible securities in the decision. A portfolio manager has to ensure at the same time, however, that the portfolio has as attractive a return–risk ratio as possible. Portfolio managers therefore have to reduce the complexity of the decision-making situation. This is achieved by combining securities with similar characteristics in classes (Bruns and Meyer-Bullerdiek 2000, p. 128). Securities may belong to more than one class. They may be classified, for example, according to sectors, countries or currencies. It can

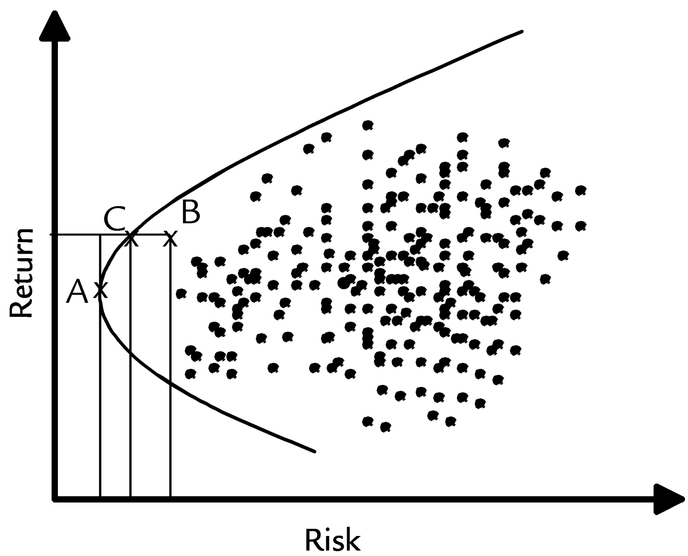

Figure 6. Return–risk characteristics of a portfolio depending on the weighting of the species.

[6] The pharmaceutical use of species could represent a special case in this context. It may be sufficient to consider one specimen of each species in the portfolio, as a second specimen may not promise any additional benefit for pharmaceutical use.

be ensured in this way that a portfolio always shows diversity in terms of sectors, countries and currencies. It is presumed, and this represents an appropriate assumption, that the stocks within a class develop similarly, i.e. the risk within their class is highly systematic. Adding more stocks of the same class will consequently contribute less to the diversification of a portfolio than adding stocks of a different class. After it has been decided how strongly a class of stocks overall is to be considered, stocks where appropriate can be selected within the sector, country and currency classes.

The manager of a biodiversity portfolio faces a similar challenge. He has to build up a portfolio which is as valuable as possible. The large number of species, genes or ecosystems does not, however, allow any simultaneous consideration of all the possible elements in his deliberations. An option is therefore to combine elements with similar characteristics in classes. The approaches to measure the genetic distance (e.g. Weitzman 1992, 1993) could be instrumental in identifying species with similar characteristics. The desired weighting of these various classes can then be decided upon in a higher-level decision. The loss of a species, for example, is accordingly easier to cope with the more species there still are in its class. In a corresponding way, the loss of a species weighs all the more heavily the more species in this class have already become extinct.[7] It has been shown in the management of stock portfolios that a top-down procedure of this kind often provides a higher contribution of value than 'stock-picking', that is to say the selection of individual shares (Brinson et al. 1991; Hensel et al. 1991).

Summary and outlook

Whenever decisions relate to a complete pool of elements and the return on the individual elements cannot be predicted with certainty, portfolio theory can be appropriately applied. Biodiversity is such a case. It is interpreted in this article as a collection of species, genes and/or ecosystems.

In economics it is assumed that decisions are determined by the expected yield and expected risk. This is also true of portfolio theory. If the decisions relate to complete portfolios, it is not the return and risk of each individual element that are of interest, but those of the complete portfolio. Decision rules, which relate to the individual elements, can then lead to incorrect, economically irrational, decisions. A prominent example in this context is the rule that for a species to be conserved, its return must exceed the costs. This approach is common in the context of the discussion of biodiversity. This is surprising, because in comparable situations a portfolio view is adopted in the theory and practice of economics.

This includes, for example, asset management among financial service providers. Professional asset managers separate the functions of analysts and portfolio managers. Analysts determine the value of a company or a stock. The decision on what

[7] It obviously cannot be concluded from this that a decline in species within a class is desirable. A decline in species within a class obviously leads to depletion of this class.

alternatives are considered in a portfolio is taken by portfolio managers, however, and because they are geared towards the success of the complete portfolio, they often also consider companies which are classified by the analysts as unattractive. No such separation has been explicitly made to date in relation to biodiversity, either in theory or in practice.

Portfolio theory makes both a positive and normative contribution for both financial portfolios and biodiversity portfolios. It firstly uncovers the relationship between the return and risk of individual elements and the return and risk of complete portfolios. Portfolio theory consequently makes available the information portfolio managers require to manage their portfolios successfully. Secondly, specific instructions for action to achieve successful portfolio management can be derived from it.

From the anthropocentric utilitarian point of view adopted in this article, genes, species and ecosystems are valuable because we may expect a future benefit. This benefit is uncertain and portfolio theory helps to optimise the risk–return ratio by ensuring that portfolios are diversified. Portfolio theory, however, diversifies the benefit of genes, species and ecosystem and not e.g. the genetic distance of the portfolio elements. If we assume that there is a negative relationship between the correlation of benefits of the portfolio elements and their genetic distance, the application of portfolio theory will not only increase the number of genes, species and ecosystems in a portfolio but also the genetic distance of the portfolio elements.

The aim of this article was to provide an introduction to the transfer of portfolio theory to biodiversity issues. There are three important possible development openings on the basis of this article.

Firstly, a general transfer which extends beyond the largely qualitative transfer of portfolio theory to biodiversity issues undertaken here should be considered. *Secondly*, the relationship between risk and return of biodiversity should be investigated more closely. As this article has shown, the distinction between systematic and unsystematic risks is of great significance in this context. In the economic sciences, use is generally made of the Capital Asset Pricing Model (CAPM) (Sharpe 1964; Lintner 1965; Mossin 1966) to establish the relationship between (systematic) risks and the value of securities. An alternative model, the Arbitrage Pricing Theory (APT) (Ross 1976), presents itself for biodiversity, however. While the CAPM is restricted to a single (systematic) risk factor, the APT permits several risk factors like e.g. different ecological impact factors. Application of APT to biodiversity can show what risks have a value-reducing effect and therefore provide important information for the optimum composition of biodiversity portfolios. *Thirdly*, some practical issues of portfolio management need to be examined. Portfolio management has the task of putting together portfolios in such a way that they meet the preferences of the portfolio holders as well as possible. Institutional issues, for example, are also to be clarified in this context.

Homogenisation of the elements of a portfolio leads to an increase in risk, without the expected return and expected risk of the individual elements having to change. This leads to an increase in risk due to systematisation of risks often remaining unobserved (Figge 1998, 2001). It is unlikely, however, that a development of this kind can be discovered from an analyst's perspective. The consequences of homogenising investment opportunities has been a topic of regular discussion for a number of years in the financial market (e.g. Brooks and Catao 2000). The management of biodiversity lags a step behind: the step from an analyst's to a portfolio manager's perspective has yet to be taken.

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References

Artuso A. 1999. The pharmaceutical value of biodiversity reconsidered. Journal of Research in Pharmaceutical Economics 9: 63–76.

Aylward B. 1995. The role of plant screening and plant supply in biodiversity conservation, drug development and healthcare. In: Swanson T.M. (ed.), Intellectual Property Rights and Biodiversity Conservation. Cambridge University Press, Cambridge, UK, pp. 93–126.

Barbier E.B. 1994. Valuing environmental functions: tropical wetlands. Land Economics 70: 155–173.

Bernholz P. and Breyer F. 1993. Grundlagen der politischen Ökonomie. Band 1: Theorie der Wirtschaftssysteme. J.C.B. Mohr, Tübingen, Germany.

Bodie Z., Marcus A.J. and Kane A. 1999. Investments. Irwin/McGraw Hill, Chicago, Illinois.

Boman M. and Bostedt G. 1995. Valuing the Wolf in Sweden. Swedish University of Agricultural Sciences, Umeä, Sweden.

Brealey R.A. and Myers S.C. 1996. Principles of Corporate Finance. McGraw-Hill, New York.

Brinson G.P., Singer B.D. and Beebower G.L. 1991. Determinants of portfolio performance II. An update. Financial Analysts Journal 47: 40–48.

Brooks R. and Catao L. 2000. The New Economy and Global Stock Returns. IMF, Washington, DC.

Brown K., Pearce D., Perrings C.A. and Swanson T.M. 1993. Economics and the Conservation of Global Biological Diversity. Global Environment Facility, Washington, DC.

Bruns C. and Meyer-Bullerdiek F. 2000. Professionelles Portofoliomanagement. Aufbau, Umsetzung und Erfolgskontrolle strukturierter Anlagestrategien. Schäffer Poeschel Verlag, Stuttgart, Germany.

Cronk Q.C.B. 1997. Islands: stability, diversity, conservation. Biodiversity and Conservation 6: 477–493.

Damodaran A. 1996. Investment Valuation. Tools and Techniques for Determining the Value of Any Asset. Wiley, New York.

Dixon J.A. and Sherman P.B. 1991. Economics of Protected Areas. A New Look at Benefits and Costs. Earthscan, London.

Drucker A.G., Gomez V. and Anderson S. 2001. The economic valuation of farm animal genetic resources. A survey of available methods. Ecological Economics 36: 1–18.

Elton E.J. and Gruber M.J. 1987. Modern Portfolio Theory and Investment Analysis. John Wiley, New York.

Figge F. 1998. Systematisierung ökonomischer Risiken durch globale Umweltprobleme. Gefahr für die Finanzmärkte? WWZ, Basel, Switzerland.

Figge F. 2001. Environment-induced systematisation of economic risks. In: Bouma J., Jeucken M. and Klinkers L. (eds), Sustainable Banking. Greenleaf, Sheffield, UK, pp. 268–279.

Fjeldså J. and Lovett J.C. 1997. Biodiversity and environmental stability. Biodiversity and Conservation 6: 315–323.

Fromm O. 2000. Ecological structure and functions of biodiversity as element of its total economic value. Universität Gesamthochschule Kassel, Kassel, Germany.

Garrod G. and Willis K.G. 1999. Economic Valuation of the Environment. Methods and Case Studies. Edward Elgar, Cheltenham, UK.

Garz H., Günther S. and Moriabadi C. 2000. Portfolio-Management. Theorie und Anwendung. Bankakad.-Verl., Frankfurt am Main, Germany.

Gauthier C. 1998. Donner une valeur à la biodiversité. Cahiers d'économie et sociologie rurales 46–47: 6–27.

Geisendorf S., Gronemann S., Hampicke U. and Immler H. 1998. Die Bedeutung des Naturvermögens und der Biodiversität für eine nachhaltige Wirtschaftsweise. Möglichkeiten und Grenzen ihrer Erfassbarkeit und Wertmessung. Erich Schmidt Verlag, Berlin, Germany.

Goodman D. 1975. The theory of diversity–stability relationships in ecology. The Quarterly Review of Biology 50: 237–266.

Gowdy J.M. 1997. The value of biodiversity. Markets, society, and ecosystems. Land Economics 73: 25–41.

Grinold R.C. and Kahn R.N. 2000. Active Portfolio Management. A Quantitative Approach for Providing Superior Returns and Controlling Risk. McGraw-Hill, New York.

Groombridge B. 1992. World Conservation Monitoring Centre (Cambridge) and British Museum (London) Natural History 1992. Global biodiversity. Status of the Earth's living resources. Chapman & Hall, London.

Hampicke U. 1999. The limits to economic valuation of biodiversity. International Journal of Social Economics 26: 158–173.

Hensel C., Ezra D. and Ilkiw J. 1991. The importance of the asset allocation decision. Financial Analysts Journal 47: 65–72.

Heywood V.H., Watson R.T. and United Nations Environment Programme 1995. Global Biodiversity Assessment. Cambridge University Press, Cambridge, UK.

Hobohm C. 2000. Biodiversität. Quelle & Meyer Verlag, Wiebelsheim, Germany.

Holling C.S. 1973. Resilience and the stability of ecological systems. Annual Review of Ecology and Systematics 4: 1–23.

Kaylen M.S., Wade J.W. and Frank D.B. 1992. Stochastic trend, weather and US corn yield variability. Applied Economics 24: 513–518.

Kopp R.J. and Smith V.K. 1993. Valuing Natural Assets. The Economics of Natural Resource Damage Assessment. Resources for the Future, Washington, DC.

Krüsselberg H.G. 1984. Vermögen im Systemvergleich – die Problemstellung. In: Krüsselberg H.G. (ed.), Vermögen im Systemvergleich. Gustav Fischer, Stuttgart, Germany, pp. 1–17.

Lamadji S., Fautrier A.G., McNeil D.L. and Sedcole J.R. 1995. Proposed breeding strategy for yield improvement of hexaploid triticale (× triticosecale Wittmack) 1. Genetic variability and phenotypic stability. New Zealand Journal of Crop and Horticultural Science 23: 1–11.

Laughland A.S., Musser W.N., Shortle J.S. and Musser L.M. 1996. Construct validity of averting cost measures of environmental benefits. Land Economics 72: 100–112.

Lerch A. 1999. Der ökonomische Wert der Biodiversität. In: Görg C. (ed.), Zugänge zur Biodiversität. Disziplinäre Thematisierungen und Möglichkeiten integrierender Ansätze. Metropolis Verlag, Marburg, Germany, pp. 169–186.

Lintner J. 1965. Security prices, risk and maximal gains from diversification. Journal of Finance 20: 587–615.

Mainwaring L. 2001. Biodiversity, biocomplexity, and the economics of genetic dissimilarity. Land Economics 77: 79–93.

Marggraf R. and Birner R. 1998. The Conservation of Biological Diversity from an Economic Point of View. Universität Göttingen, Göttingen, Germany.
Markowitz H.M. 1952. Portfolio selection. Journal of Finance 7: 77–91.
Markowitz H.M. 1959. Portfolio Selection. Efficient Diversification of Investments. Wiley & Sons, New York.
Mason R. 1996. Market failure and environmental degradation. In: Swanson T.M. (ed.), The Economics of Environmental Degradation. Tragedy for the Commons? Edward Elgar, Cheltenham, UK, pp. 29–54.
Mendelsohn R. and Balick M. 1996. The value of undiscovered pharmaceuticals in tropical forests. Economic Botany 49: 223–228.
Mossin J. 1966. Equilibrium in a capital asset market. Econometrica 34: 768–783.
Myers N. 1980. The Sinking Ark. A New Look at the Problem of Disappearing Species. Pergamon Press, Oxford, UK.
Nagi K.S. and Khehra A.S. 1996. Effect of selection on the components of genetic variability for grain yield and its components under two plant densities in maize (zea mays L.). The Indian Journal of Genetics and Plant Breeding 56: 129–136.
Naylor R., Falcon W. and Zavaleta E. 1997. Variability and growth in grain yields, 1950–1994. Does the record point to greater instability? Population and Development Review 23: 41–58.
Nunes P.A.L.D. and van den Bergh J.C.J.M. 2001. Economic valuation of biodiversity: sense or nonsense? Ecological Economics 39: 203–222.
Olson R.L. 1999. Olson on asset allocation. Investment Policy 2: 81–97.
Organization for Economic Cooperation and Development 1992. Benefits Estimates and Environmental Decision Making. OECD, Paris, France.
Pearce D. 1995. Blueprint 4. Capturing Global Environmental Value. Earthscan, London.
Pearce D. and Barbier E.B. 2000. Blueprint for a Sustainable Economy. Earthscan, London.
Pearce D. and Puroshothaman S. 1995. The economic value of plant-based pharmaceuticals. In: Swanson T.M. (ed.), Intellectual Property Rights and Biodiversity Conservation. Cambridge University Press, Cambridge, UK, pp. 127–138.
Pearce D. and Turner R.K. 1990. Economics of Natural Resources and the Environment. Johns Hopkins University Press, Baltimore, Maryland.
Perrings C. 1995. The economic value of biodiversity. In: Heywood V.H. and Watson R.T. (eds), Global Biodiversity Assessment. Cambridge University Press, Cambridge, UK, pp. 823–914.
Perrings C. 1998. Resilience in the dynamics of economy–environment systems. Environmental and Resource Economics 11: 503–520.
Perrings C. and Stern D.I. 1998. Modelling loss of resilience in agroecosystems. Rangelands in Botswana. Environmental and Resource Economics 16: 185–210.
Pirscher F. 1997. Möglichkeiten und Grenzen der Integration von Artenvielfalt in die ökonomische Bewertung vor dem Hintergrund ethischer Normen. Peter Lang, Frankfurt am Main, Germany.
Plän T. 1999. Ökonomische Bewertungsansätze biologischer Vielfalt. GTZ, Eschborn, Germany.
Polasky S., Camm J.D. and Garber-Yonts B. 2001. Selecting biological reserves cost-effectively. An application to terrestrial vertebrate conservation in Oregon. Land Economics 77: 68–78.
Porter P.M., Lauer J.G., Huggins D.R., Oplinger E.S. and Crookston R.K. 1998. Assessing spatial and temporal variability of corn and soybean yields. Journal of Production Agriculture 11: 359–363.
Rappaport A. 1986. Creating Shareholder Value. The New Standard for Business Performance. The Free Press, New York.
Ross S.A. 1976. The arbitrage theory of capital asset pricing. Journal of Economic Theory 13: 341–360.
Schäller G. 1991. Wirkung der Umweltfaktoren und Anpassung der tierischen Organismen. In: Schubert R. (ed.), Lehrbuch der Ökologie. Gustav Fischer Verlag, Jena, Germany, pp. 173–181.
Schmidt R.H. and Terberger E. 1997. Grundzüge der Investitions- und Finanzierungstheorie. Gabler, Wiesbaden, Germany.
Schurle B. 1996. The impact of size on yield variability and crop insurance premiums. Review of Agricultural Economics 18: 415–422.
Sharpe W.F. 1964. Capital asset prices: a theory of market equilibrium under conditions of risk. Journal of Finance 19: 425–442.

Sharpe W.F. 1970. Portfolio Theory and Capital Markets. McGraw-Hill, New York.
Simpson D.R., Sedjo R.A. and Reid J.W. 1996. Valuing biodiversity for use in pharmaceutical research. Journal of Political Economy 104: 163–185.
Smith K.V. 1996a. Estimating Economic Values for Nature. Methods for Non-market Valuation. Edward Elgar, Cheltenham, UK.
Smith K.V. 1996b. Resource evaluation at a crossroads. In: Smith K.V. (ed.), Estimating Economic Values for Nature. Methods for Non-market Valuation. Edward Elgar, Cheltenham, UK, pp. 3–41.
Solow A.R., Polasky S. and Broadus J. 1993. On the Measurement of Biological Diversity. Journal of Environmental Economics and Management 24: 60–68.
Stevens T.H., DeCoteau N.E. and Willis C.E. 1997. Sensitivity of contingent valuation to alternative payment schedules. Land Economics 73: 140–148.
Swanson T.M. 1991. Conserving biological diversity. In: Pearce D. (ed.), Blueprint 2. Greening the World Economy. Earthscan, London, pp. 181–208.
Swanson T.M. 1992. Economics of a biodiversity convention. Ambio 21: 250–257.
Swanson T.M. 1994. The International Regulation of Extinction. New York University Press, New York.
Swanson T.M. 1996. The economics of environmental degradation. An institutional approach. In: Swanson T.M. (ed.), The Economics of Environmental Degradation. Tragedy for the Commons? Edward Elgar, Cheltenham, UK, pp. 1–28.
Swanson T.M. 1997. Global Action for Biodiversity. An International Framework for Implementing the Convention on Biological Diversity. Earthscan, London.
Swanson T.M. 1999. Why is there a biodiversity convention? The international interest in centralized development planning. International Affairs 75: 307–331.
Swanson T.M. and Goeschl T. 1998. The Management of Genetic Resources for Agriculture. Ecology and Information, Externalities and Policies. CSERGE, Norwich, UK.
Tobin J. 1958. Liquidity preference as behavior towards risk. Review of Economic Studies 25: 65–86.
Vogel G. and Angermann H. 1990. Dtv-Atlas zur Biologie. Tafeln und Texte. Band 2. Dt. Taschenbuch-Verlag, München, Germany.
Volkart R. 1998. Shareholder value & Corporation Valuation. Finanzielle Wertorientierung im Wandel. Versus, Zürich, Switzerland.
Weikard H.-P. 1998. Der Wert der Artenvielfalt. Eine methodische Herausforderung an die Ökonomik. Zeitschrift für Umweltpolitik & Umweltrecht 21: 263–273.
Weikard H.-P. 2002. Diversity functions and the value of biodiversity. Land Economics 78: 20–27.
Weitzman M.L. 1992. On diversity. Quarterly Journal of Economics 107: 363–405.
Weitzman M.L. 1993. What to preserve? An application of diversity theory to crane conservation. The Quarterly Journal of Economics 108: 157–183.
Wood P.M. 1997. Biodiversity as the source of biological resources: a new look at biodiversity values. Environmental Values 6: 251–268.