Chapter 3
Economic Potential of Site-Specific Fertiliser Application and Harvest Management

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Abstract Site-specific fertiliser management has been discussed as an information-based farming concept that uses plant- and soil-specific information. However, agricultural practice has shown that, because of limited profitability, the adoption of site-specific fertiliser management often does not meet expectations. This chapter describes a framework for the economic assessment of site-specific fertiliser application and harvest management, provides an overview of selected studies and shows the future perspective of the technologies.

We concluded that precision farming technologies that aim to identify the economically optimal input rate (e.g. site-specific fertiliser application) often fail to provide considerable economic advantages for the farmer. This phenomenon can be explained by flat payoff functions, which are relevant for many agricultural production processes. Economically more promising from a theoretical point of view are precision farming approaches that enable higher product prices by achieving specific product qualities (e.g. site-specific harvest management). However, available studies currently do not provide empirical support for this theoretical conclusion.

Keywords Economic evaluation • Nitrogen fertiliser • Precision farming • Smart farming • Site-specific production functions

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3.1 Introduction

During the last two decades, the emergence of information technologies and geographic information systems has triggered technological solutions for information-based agricultural management systems. These systems have the potential to increase the efficiency of agricultural systems and contribute to economic and environmental gains. Because of the economic and environmental potential of these systems, two recent reports analyse precision farming technologies from a policy perspective. Because of a request from the European Parliament's Committee on Agriculture and Rural Development, Zarco-Tejada et al. (2014) published a study titled: "Precision Agriculture: An opportunity for EU farmers – Potential support with the CAP 2014–2020". The Organisation for Economic Co-operation and Development (OECD) has released a report discussing "Farm Management Practices to Foster Green Growth" where the question was raised: "Is precision agriculture the start of a new revolution?" (OECD 2016, p. 137). Despite the great interest in precision farming technologies shown by politicians and by researchers, the adoption of many of these technologies is still limited (OECD 2016). Some of the major constraints for adoption of precision farming technologies are the complexity of the technology (including incompatibility of components), time requirements, high start-up costs, and lack or uncertainty of profitability, among others (Griffin et al. 2004; Khanna et al. 1999; Reichardt et al. 2009; Robertson et al. 2012). Therefore, the aim of this chapter is to analyse the economics of different precision farming technologies as a major determinant for their adoption. Studies addressing different aspects of the economic potential of site-specific fertiliser application and harvest management were analysed, including the potential for using information technologies in farm management. The remaining part of this chapter is organised as follows. In Sect. 3.2, a framework for the economic assessment of site-specific fertiliser application and harvest management is presented. In the section that follows, selected studies that analyse the economic benefits of site-specific fertiliser application and harvest management are discussed. The chapter closes with some general conclusions.

3.2 Framework for Economic Assessment

According to Meyer-Aurich et al. (2008) a comprehensive economic assessment of precision farming technologies at the farm level needs to take into account all relevant monetary and non-monetary aspects, including effects on crop yield, input use, changes in management and the quality of work. Table 3.1 provides an overview of the costs and possible benefits of precision farming technologies. Four different types of costs that arise from farm-level implementation of precision farming technologies can be distinguished. Information costs are associated with the necessary investment in technologies or equipment rental fees necessary to ascertain specific information.

Table 3.1 Costs and possible benefits from Precision Farming

Costs of precision farming	Possible benefits
Information costs	Crop yield effects
Costs of data processing	Changes in input use
Costs of adapted management	Changes in management
Learning costs	Quality of work
	Production risk mitigation

Source: Meyer-Aurich et al. (2008), modified

Costs for data processing include costs for specific software or hardware products, but also opportunity cost for time needed to develop site-specific management schemes. Precision farming involves a change in management which may incur specific costs. In addition, learning costs, including opportunity costs because of inefficient use of precision farming technologies, need to be taken into account, particularly in the introduction phase.

Possible benefits of precision farming stem from crop yield effects and reduced input use from more efficient farming; more efficient farm management with improved communication possibilities and higher quality of work with machine-guided systems. The implementation of precision farming concepts may mitigate production risks because inputs are applied only where they are needed. While risk mitigation with precision farming is intuitive, the implementation of precision farming typically requires substantial investments that may increase financial risk (Lowenberg-DeBoer 1999). Investments in precision farming are further associated with irreversibility of the capital cost, which should be taken into account where appropriate. Farmers might prefer to wait for better information on the costs and benefits of the new technology before investing in precision farming technologies (Tozer 2009).

While the costs of precision farming technologies can, in many cases, be estimated precisely, it is more challenging to evaluate the response of the system to improved management. Production function analysis can be applied to assess the effects on crop yield and changes in input use from site-specific nitrogen management (Bachmaier and Gandorfer 2009; Meyer-Aurich et al. 2010b; Bullock et al. 2002, Rogers et al. 2016). The analysis of production functions helps us to gain insight into input–output relationships to enable the choice of the optimal rate of input as a function of the price of input and output. Site-specific production functions can be estimated, for instance, from field trial data (e.g. nitrogen rate trials) or from data simulated with crop growth models.

In rain-fed plant production systems, the response to inputs varies substantially from year to year, which complicates the determination of economically optimal rates of input. However, from an ex-post perspective, the analysis of production functions helps us to understand the crop response to inputs, and can be used to identify the economic potential of site-specific fertilization strategies. In such ex-post analyses, it is typically assumed that economically optimal rates of input are applied in both site-specific and uniform management. Therefore, it is important to consider that the results show the theoretical ex-post economic potential of site-specific management. In practical agriculture, it is not possible to determine ex-ante exact economic optimum input rates especially for nitrogen because of unpredictable weather events. This is true for site-specific management as well as for uniform management. Thus, there will always be a difference between the theoretically optimal fertiliser rate and the realized fertiliser rate. Whether the theoretically optimal fertiliser rate can be realised in practice depends on the applied site-specific technology, implemented decision algorithms and other factors, such as a uniform reference system.

Bachmaier and Gandorfer (2009) presented an approach based on production function analysis to test if there is a significant difference between site-specific economically optimum nitrogen rates. Significant differences in economically optimum input rates are a prerequisite for the profitability of site-specific fertiliser management. However, it is important to recognize that yield heterogeneity does not necessarily lead to significant differences in site-specific economic fertiliser rates (Bachmaier and Gandorfer 2009). From an economic point of view, it is important that site-specific production functions have different slopes, which cause different marginal yield responses to an additional unit of input. Thus, yield heterogeneity identified, for instance, with yield maps from combine harvesters cannot serve as a robust indicator for the profitability of site-specific fertiliser management. In this context, Rogers et al. (2016) have suggested a new metric to describe the flatness of site-specific payoff functions in order to estimate better the economic potential of site-specific input management at the field level. The metric is called relative curvature, and the authors found that the metric could help to identify field heterogeneity from an economic perspective. Relative curvature "is obtained by calculating the area lying between the graph of the pay-off function and a horizontal line that is tangent to this graph at the point of maximum pay-off (profit) over a given range of input values" (Rogers et al. 2016, p. 111).

An alternative way to assess the economic benefits of site-specific management approaches (e.g. a commercially available sensor system for nitrogen fertilization) compared to uniform management is to conduct field trials (e.g. strip trials) where different systems are tested and compared. In such trials, uniform management is often defined as farmers' usual practice. This is important to consider when such results are discussed in comparison to the potential analysis based on site-specific production functions described previously.

3.3 Analysis of Studies

Various studies have shown mixed results of the profitability of site-specific management. Lambert and Lowenberg-DeBoer (2000) reviewed 108 studies on the economics of site-specific management strategies. Of the 34 studies that deal with site-specific fertilization, 65% showed positive economic effects, 18% showed negative effects and 17% of the studies reviewed described mixed results (see

Lambert and Lowenberg-DeBoer 2000, p. 14). Bongiovanni and Lowenberg-DeBoer (2004) provided an extensive review of precision agriculture studies to analyse the potential contribution of precision agriculture technologies to a more sustainable agricultural production system. They concluded that site-specific management of inputs, like fertilisers and chemicals, reduce negative impacts on the environment. However, their case study in Argentina showed that the profitability is only modest compared to whole field management. Also, Diacono et al. (2013) concluded from a review of studies about site-specific nitrogen fertilisation of wheat that these approaches do not necessarily lead to economic advantages. In several more recent studies, the economic potential of site-specific fertiliser management is analysed both theoretically and empirically based on improved technological possibilities, which will be discussed in detail in the following sections.

3.3.1 Site-Specific Nitrogen Fertilization

Schneider and Wagner (2008) investigated the economics of site-specific fertilization strategies. They compared a sensor and a mapping approach for site-specific nitrogen fertilization in winter wheat and canola. Based on a series of eight experiments, the partial budgeting of the mapping approach resulted in an average negative contribution to profit (−14 € ha^{-1}), whereas the sensor approach provided a positive contribution to profit (16 € ha^{-1}) (Schneider and Wagner 2008, p. 419). These values do not include costs for the sensor technologies necessary for information gathering and variable-rate application. The per ha cost assumptions for the sensor approach depend on the acreage on which the technology is used, ranging from about 6 to 65 € ha^{-1} for the use on 1000 to 100 ha, respectively (Schneider and Wagner 2008, p. 426). A more sophisticated and information-intensive site-specific fertilization approach based on a neural network and decision tree algorithms resulted in the highest net profitability when compared to other fertiliser management systems. The economic advantage of this approach (partial budget) was 46 € ha^{-1} compared to uniform management, and 29 € ha^{-1} compared to the sensor approach (Schneider and Wagner 2008, p. 419). These results are in line with the findings from theoretical work by Bullock et al. (2002), who found increasing marginal profits of site-specific nitrogen fertiliser management with increasing information. However, the maximum gross economic effect was only about 7 US$ ha^{-1} when costs for information gathering were excluded (Bullock et al. 2002). Another study investigated the economic return of site-specific fertilization of nitrogen and phosphorus in Western Australia (Lawes and Robertson 2011). They found that site-specific fertiliser management provided economic benefits on six of the 20 fields investigated with an average of 15 AU$ ha^{-1} (ca. 11 € ha^{-1}), however, costs for information gathering and variable-rate application were again excluded. Lawes and Robertson (2011) also addressed the question of to what extent an increase in the number of management zones can contribute to higher economic returns. They found diminishing marginal returns with increasing number of management zones, which provides an argument for the importance to address the major managing zones. This conclusion is in contrast to the results of Schneider and Wagner (2008) and Bullock et al. (2002) discussed above. Therefore, from an economic point of view, it remains an open question as to how precise (e.g. the number of different management zones) site-specific fertiliser management should be.

It is further notable that studies based on field trials often show higher economic benefits of site-specific farming than the theoretical potential benefits derived from production function analysis (Silva et al. 2007, Meyer-Aurich et al. 2008). This is somewhat surprising, but can be explained with the reference (uniform management) chosen for the economic comparison. For example, if a uniform management system is compared with a site-specific management system, both systems rely on different sources of information. For example, while a site-specific management system uses a sensor, a uniform management system might rely on expert knowledge. If the uniform management is performed badly, the difference in the economic performance of the systems compared is higher. It can be assumed further that the implementation of site-specific fertilization contributes not only to a better consideration of production factors like fertilisers, but also to better management in general. In the analytical ex-post analyses, it is difficult, if not impossible, to distinguish between both effects. Thus, comparisons of site-specific and uniform management based on field experiments should be analysed with care.

The rather low economic advantages question the site-specific management of fertilisers from an economic point of view, which is in line with the conclusions of Oleson et al. (2004), and Liu et al. (2006). Based on payoff function analysis, Pannell (2006, p. 553) concluded that: “the benefits of using ‘precision farming’ technologies to adjust production input levels are often low”. This conclusion results from the insight that payoff functions are often flat in the area of the economic optimum input level and, therefore, deviations from the economically optimum input level are in many cases associated with only marginal economic losses (Pannell 2006). Figure 3.1 illustrates an example of a flat payoff function and shows that, for instance, a deviation of 20% from the economic optimum input rate reduces the payoff only marginally.

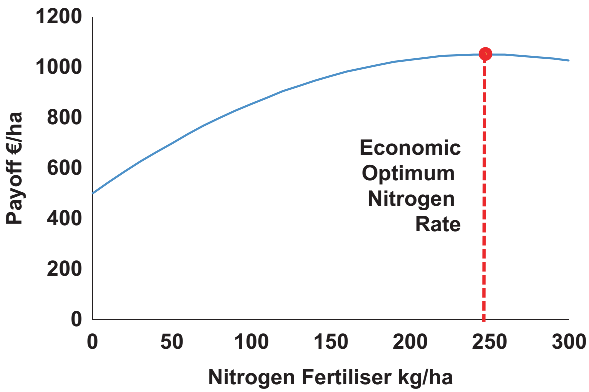

Fig. 3.1 Payoff for winter wheat as a function of nitrogen fertiliser rate (crop quality not considered). Note: The figure is based on a published nitrogen production function for the winter wheat cultivar Contur (Meyer-Aurich et al. 2010b) (Source: own illustration)

Site-specific fertiliser management, however, could result in a higher economic advantage if farmers were faced with environmental restrictions or had to internalize the environmental damage costs of fertilization. In this context Gandorfer et al. (2003) showed, for instance, that site-specific nitrogen management leads to lower abatement costs compared to uniform management when environmental targets (e.g. nitrate concentration in seepage water) have to be met. Also Rogers et al. (2016) conclude that if farmers must internalize negative external effects of sub-optimal fertiliser application, the importance of identifying economic optimum input levels increases and therefore, the economic benefit of site-specific fertiliser management.

3.3.2 Site-Specific Management with Respect to Crop Quality

An additional increase in benefit of site-specific fertilization may be realized if higher crop qualities can be assured and thus, the crop can be sold at higher prices. In this situation, the payoff function jumps to a higher level which may result in higher profit margins. This can be achieved by site-specific nitrogen management in wheat production considering site-specific protein functions or by quality specific harvest.

3.3.2.1 Site-Specific Nitrogen Management with Respect to Protein Concentration

Gandorfer and Rajsic (2008) provided an empirical example for such a situation where the payoff function jumps to a higher level when a specific protein concentration threshold is met and, therefore, the winter wheat price increases (Fig. 3.3). The analysis is based upon estimated winter wheat yield and protein response functions to nitrogen fertilisation (Fig. 3.2) for two experimental sites,- Wolfsdorf and Betzendorf (Bavaria, Germany). The experimental field in Wolfsdorf shows a higher yield potential because of better growing conditions in terms of precipitation, average temperature and soil conditions (Gandorfer and Rajsic 2008).

The extent of the jumps in the payoff function depends on the underlying yield and protein response functions, but also on the protein premium schemes. Because protein premium schemes differ both from year to year and between crops, the economic benefits of accounting for crop quality in terms of protein concentration also vary from year to year. For illustration, Fig. 3.4 shows producer prices for different quality grades of winter wheat (A, B and Feed Quality) in terms of protein concentration. To be graded as “A-Quality’ wheat, the protein concentration must be above 13.5%. Wheat with a protein concentration in the range between 12% and 13.5% falls into the “B-Quality’ category. Clearly, there are years in which a high protein concentration is beneficial (e.g. 2010) and years with marginal price differences only among different qualities (e.g. 2012).

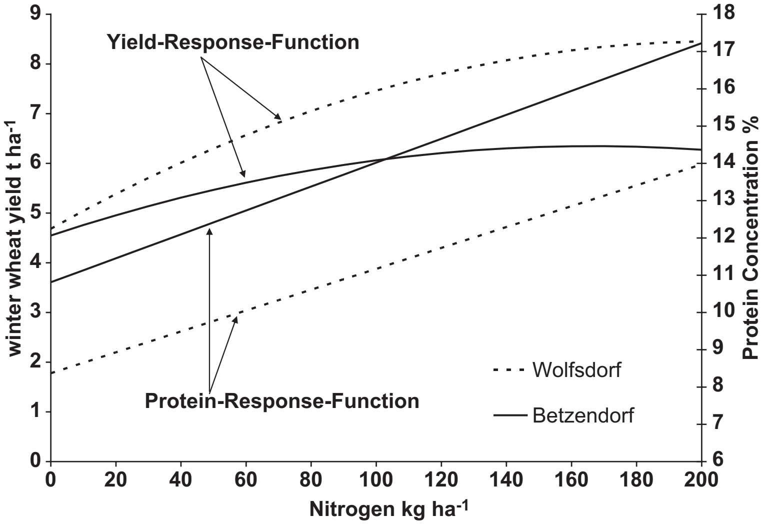

Fig. 3.2 Estimated average (2000–2002) winter wheat yield and protein response functions to nitrogen fertilisation (Source: Gandorfer and Rajsic 2008)

Fig. 3.3 Average net return function calculated for price regimes from 2004 and 2005 for the experimental sites in Wolfsdorf and Betzendorf. Net return is defined as crop revenue minus nitrogen fertiliser cost (Source: Gandorfer and Rajsic 2008)

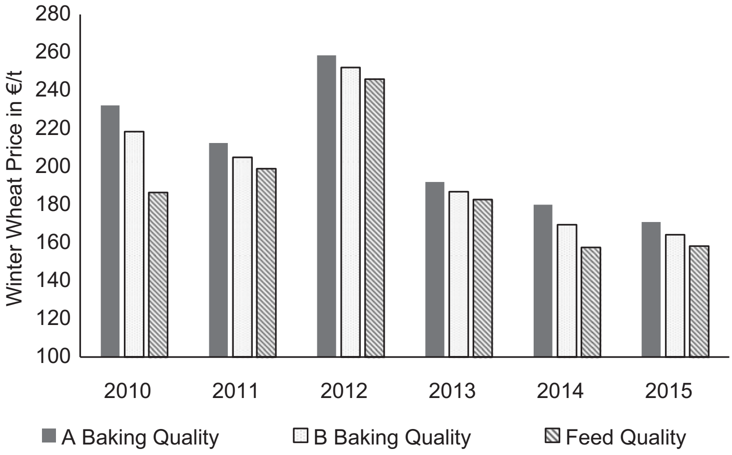

Fig. 3.4 Protein premium schedules for Bavaria, Germany, Source LfL (2016)

Meyer-Aurich et al. (2010a) provided an economic analysis of site-specific fertiliser strategies with consideration of crop quality based on data from an on-farm field experiment. In their study they proposed a spatial econometric approach to analyse crop yield and quality response to nitrogen fertiliser to improve nitrogen management. However, they did not find a clear economic advantage of site-specific fertilization when crop quality was considered in terms of the German protein premium scheme. The gross economic potential of site-specific nitrogen management with respect to protein concentration was estimated to be 2.57 € ha^{-1} only without considering the fixed costs associated with the site-specific fertiliser application approach.

3.3.2.2 Site-Specific Harvest Management (Grain Segregation by Protein Concentration)

The economic effects of grain segregation and blending by protein concentration has been addressed by various authors in the past (e.g. Sivaraman et al. 2002). These analyses were performed either at the level of the grain elevator or at later stages in the grain value chain. New precision farming technologies now make it possible to realize site-specific harvest management with the idea of shifting back the economic benefits of grain segregation and blending from the grain elevator to the farm operations. Thus, several authors have studied the economic effects of various approaches of site-specific harvest management and grain segregation recently (e.g. zone harvesting or separation in harvester) (Tozer and Isbister 2007; Meyer-Aurich et al. 2010b; Martin et al. 2013).

Meyer-Aurich et al. (2010b) discussed that 'on the go' sensors could help to separate grain quality during harvest, and different fractions could be sold at different prices. In contrast to the site-specific fertiliser strategy, this strategy may have a higher economic effect, especially if the necessary crop quality cannot be achieved for the whole field and price incentives for higher grain qualities are set. Therefore, the positive economic effect of site-specific harvest management is based on a higher average crop price compared to whole field harvest. Because a higher average crop price, site-specifc harvest management can shift the site-specific payoff function to a higher level. Martin et al. (2013) have identified three important variables that determine the economic benefits of grain segregation at the field level. In addition to the average protein concentration of the field (1) and within-field variability of protein concentration (2), the price premiums for protein (3) are relevant.

Meyer-Aurich et al. (2010b) constructed model calculations based on fertiliser response experiments that show the possible crop yield and grain quality response of wheat to nitrogen fertiliser supply. Based on virtual fields with heterogeneous response, the economic gross benefit of site-specific harvest management resulted in an advantage ranging from −2 € ha^{-1} to 33 € ha^{-1}. Although the relative profitability of site-specific harvest management is limited, it can have a risk reducing effect. This is demonstrated by the example shown in Fig. 3.5 for two price scenarios for baking quality wheat.

With uniform harvest (solid line), the highest net returns (above fertiliser cost) can be obtained with a fertiliser rate of about 170 kg N per ha, which is about 80 € ha^{-1} higher than the maximum net return for feed quality at a premium for baking quality of 0.9 € per ton wheat (top graph in Fig. 3.5). This premium was the average premium received by Bavarian farmers from 2009 to 2016. At a lower protein premium (bottom graph in Fig. 3.5), returns above fertiliser costs are reduced accordingly. Since parts of the field achieve baking quality at N rates lower than 170 kg ha^{-1}, at these fertiliser rates the possibility of separating different qualities can generate a higher profit compared to a uniform harvest by selling a fraction of the harvest as quality wheat. This advantage is illustrated with the dotted line in Fig. 3.5. Even though the maximum net return above fertiliser cost with site-specific harvest management does not exceed the maximum of the net return with uniform harvest, the window of fertiliser levels that result in higher net returns is substantially bigger. In other words, within a window of nitrogen rates from 158 and 179 kg N ha^{-1}, net returns are higher with site-specific harvesting because within this range baking quality can be achieved in one of the modelled parts of the field only. The separation of the higher quality grains results in a higher economic return for this part of the grains and averaged over the whole field (dotted line). Without grain separation, all grains are assumed to be sold at a lower price since the average protein content is below the threshold.

The results indicate that separating different grain qualities during harvest can assure high profits, even when the protein requirement is not achieved for the whole field. This may reduce the producer's risk, i.e. failure to achieve the required protein quality in the whole field.

Tozer and Isbister (2007) evaluated the economic benefits of harvesting by management zones, and identified situations in terms of field layout, and yield or quality scenarios where site-specific harvest management can generate economic benefits. The economic effects of harvesting by management zones ranged from −8 AU$ ha^{-1} to 30 AU$ ha^{-1} (ca. –6–20 € ha^{-1}) for the different scenarios analysed (Tozer and Isbister 2007, p. 158). The assessment included additional costs distances trav-

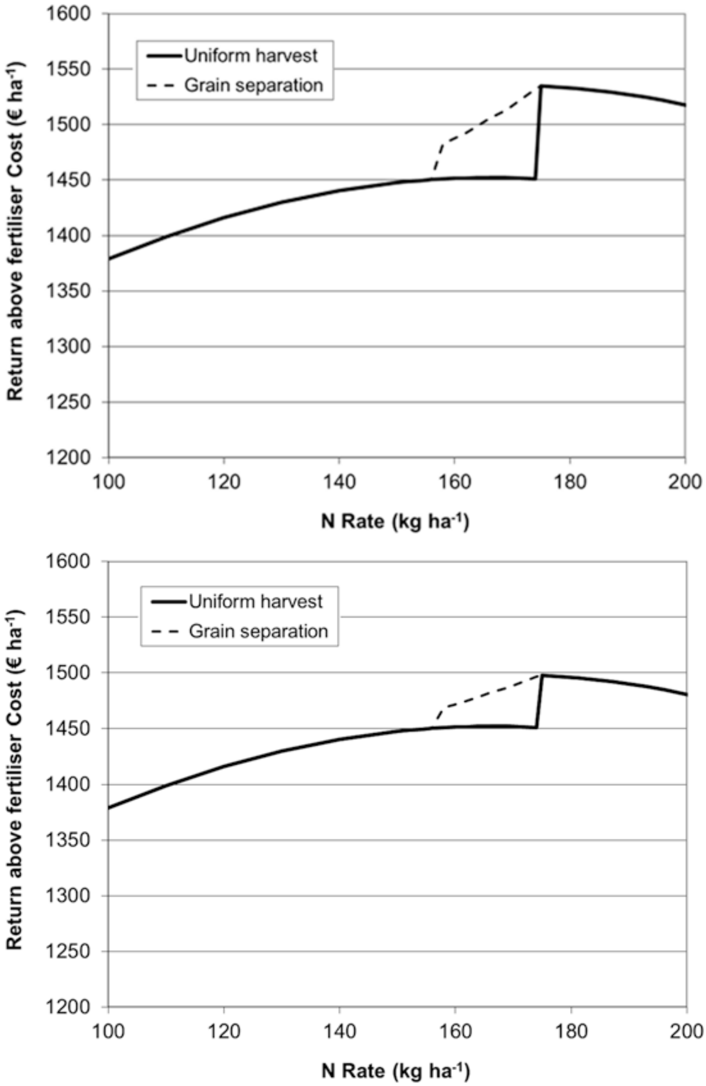

Fig. 3.5 Returns above fertiliser costs with uniform and separate harvest management with premiums for baking quality wheat of 0.9 € (top graph) and 0.5 € (bottom graph) per ton of wheat (Based on model calculations in Meyer-Aurich et al. 2010b)

elled that arise from harvesting by management zone. The authors showed that because of the underlying protein premium schedules and additional harvesting costs, blending the grain from the whole field can lead to a higher gross crop revenue compared to harvesting by management zone.

A limitation of available studies is that they often do not account for the total cost of site-specific harvest management including technology costs for grain segregation and additional storage and logistic costs. Particularly, additional storage and logistic costs may be high, and can diminish the economic benefits of site-specific harvest management. The impact of site-specific management approaches that consider grain quality (including separate harvest) on the environmental has not yet been studied sufficiently. While it is intuitive to assume that site-specific management can save on unnecessary amounts of fertiliser where they are not needed, site-specific management could also enable the exploitation of economic potentials leading to negative environmental effects.

3.4 Conclusions

Economic benefits of site-specific fertiliser management are often limited because of flat site-specific payoff functions in the area where the economic optimum is located. Even though information technologies are expected to become less cost-intensive over time, this will not overcome the general limitation of flat site-specific payoff functions. Furthermore, the necessary sensor technologies and advanced site-specific application technologies may not necessarily become cheaper in the future. Therefore, from an economic point of view future potentials of precision farming are, particularly given for technologies which generate a new payoff function, at a higher level rather than technologies which aim at improving management decisions (see also Gandorfer et al. 2011, Pannell 2006). One example of such a technology might be site-specific harvest management. However, available studies currently do not prove substantial economic advantages of site-specific harvest management, but do show a potential risk-reducing effect. Improved efficiency in agricultural systems with precision farming may provide environmental benefits. Further research is required to provide an economic assessment of this potential positive externality. The advantage of site-specific fertiliser management and harvest management may be higher if farmers were faced with environmental restrictions or in a situation where the costs of environmental damage from fertiliser use must be accounted for.

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