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Science for food, climate protection and welfare: An economic analysis of plant breeding research in Germany

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ABSTRACT

We analyze the economic effects of plant breeding research in Germany. In addition to market effects, for the first time also effects of reduced CO_2 emissions due to productivity increases are being quantified. The analysis shows that investments in German plant breeding research in the period 1991–2010 have reduced the global expansion of agricultural area by 1–1.5 million hectares. This has led to reduced CO_2 emissions of 160–235 million tons. The economic value generated by plant breeding research, through increased production and reduced greenhouse gas emissions, is estimated at 10.8–15.6 billion EUR in the same period. This can be translated into a social rate of return on research investment in the range of 40–80% per year. Projections for the period 2011–2030 generate a return rate in the range of 65–140% per year. Investments into plant breeding research in Germany are highly profitable from a societal point of view. At the same time, our results show significant under-investments in agricultural research in Germany. These results provide a good justification for policy-makers to reverse funding cuts for public agricultural research over the last decades and to improve institutional conditions for private research, e.g. through better protection of intellectual property rights.

1. Introduction

The economic conditions for world agriculture have changed dramatically. This also holds true for agriculture in the European Union. The secular trend of falling agricultural prices (i.e. adjusted for inflation) has come to an end. Since the turn of the millennium the prices for major agricultural commodities have steadily increased. This development is expected to continue, as global demand for agricultural products is rising faster than supply. Main reasons are rapid growth of population and income in many developing and emerging economies.

In the first half of the 21st century global food demand will double. Rising demand can be fulfilled either by expanding agricultural land or raising agricultural productivity. The first option is limited, as suitable areas for agricultural expansion are scarce. The most productive areas are already in use. In many parts of the world there are hardly any unused agricultural land reserves which could be mobilized. Some available areas, like tropical forests or savannas, should rather not be used for reasons of biodiversity conservation or climate protection.

Over the last 50 years, the largest contribution to growth in world agricultural output was due to productivity growth. This accounted for about 80% of additional output, while only about 20% was due to area expansion (FAO, 2010). In the future, global agriculture has to rely even more on increasing productivity, if growing demand from a rising world population is to be met (FAO, 2009). Without immediate and decisive action, the required productivity growth will not be achieved. Since the second Green Revolution in the 1960s and 1970s, global agricultural productivity growth has slowed down. Between 1960 and 1990 agricultural productivity grew by about 4% per year. It has now fallen to 1% per year. In the European Union growth rates are even lower, at about 0.6% per year (von Witzke and Noleppa, 2010). Public policies for pollution reduction within the EU may also have an effect on agricultural productivity, depending on specific regional circumstances (Falavigna et al., 2013).

One major reason for reduced technological progress is reduced investments in agricultural research and development (R&D). Under conditions of excess supply in the EU, North America and elsewhere, public investments in agricultural research activities have been scaled down. This has been particularly true for investments which are specifically aiming at productivity increases (Alston et al., 2010; Pardey, 2009). Neglecting agricultural research is one of the major reasons, why the EU has become the world's biggest net importer for agricultural commodities. The land area, which the EU

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uses outside its territory for fulfilling domestic demand, meanwhile amounts to more than 30 million ha, i.e. an area comparable to the size of Germany (von Witzke and Noleppa, 2010).

The majority of poor countries in the world used to be net exporters of food in the trade relationships with rich, industrialized countries. Now many of them are net importers of food. The import gap of poor countries will increase fivefold by 2030, compared to the year 2000 (FAO, 2003). Even under the best of a range of plausible projections, most poor countries will not be able to fulfill their quickly growing demand from domestic production over the coming decades. Their fast growing import gap can only be filled, if the rich countries also produce more and export agricultural commodities.

Moreover, growing EU net imports also have environmental consequences, as additional agricultural areas in other parts of the world are taken into production. Following Searchinger et al. (2008), the phenomenon of shifting production to other world regions has been labeled “indirect land use change” (iLUC). Large amounts of carbon dioxide (CO_2) are released into the atmosphere due to tropical deforestation and conversion of forest and grass land into cropland. Expansion of agricultural areas contributes more to global anthropogenic greenhouse gas emissions than industry or transportation (e.g. IPCC, 2014; Stern, 2007). Agricultural innovation and related productivity increases, also in rich countries like Germany, play an important role for global food security as well as reduction of CO_2 emissions. In this context, plant breeding research is crucial. Recent research has shown that the share of plant breeding and plant-genetic improvements in total productivity growth in agriculture has increased over time (e.g. Ahlemeyer and Friedt, 2010; Mackay et al., 2009; Webb, 2010).

In this paper, we conduct a classical cost–benefit analysis of plant breeding research in Germany, including direct market effects as well as reductions in CO_2 emissions due to indirect land use changes. We make use of a unique primary data set on research expenditures by private breeding enterprises in Germany. Changes in consumer and producer welfare due to productivity increases are quantified and compared to investments into research and development. Thus, overall welfare changes for society can be derived, also including the monetary benefits from reduced greenhouse gas emissions.

In the next section, we present our methodological approach. Section 3 provides an overview of data sources for calculation of productivity changes and agricultural research investments in Germany. In Section 4 we present results of the analysis, followed by a discussion. Based on our quantitative results, conclusions are drawn with a focus on implications for national and international research policy.

2. Theoretical basis and methods

The starting point of our analysis is the change in total factor productivity (TFP) per hectare (ha) in agriculture. This indicates which part of observed changes in land productivity is caused by genuine innovation, and cannot be related to increased factor use intensity:

$$dTFP/TFP = dQ/Q - (dI/I) * SI - (dL/L) * SL \tag{1}$$

with: Q = Index of production, I = Index of all intermediate inputs used (e.g. fertilizer, pesticides, machinery), L = Index of labor input, S = Expenditure shares of specific production factors.

Changes in TFP growth can then be used in a market modeling framework to assess social welfare changes. The conceptual approach of this analysis is shown in Figs. 1 and 2 for the simplest case of an agricultural sector without international trade. Figure 1 shows a typical market diagram, where the demand function of consumers (D) represents the willingness-to-pay for alternative quantities of good Q. The total willingness to pay for the amount Q1 is the area under the demand function between the origin and Q1. As a matter of fact, consumers only pay the market equilibrium price P1 for the total amount Q1, i.e. the rectangle P1 * Q1. The difference between the willingness-to-pay of consumers and what they really pay is the triangle between the demand function and P1 (also called “consumer surplus”).

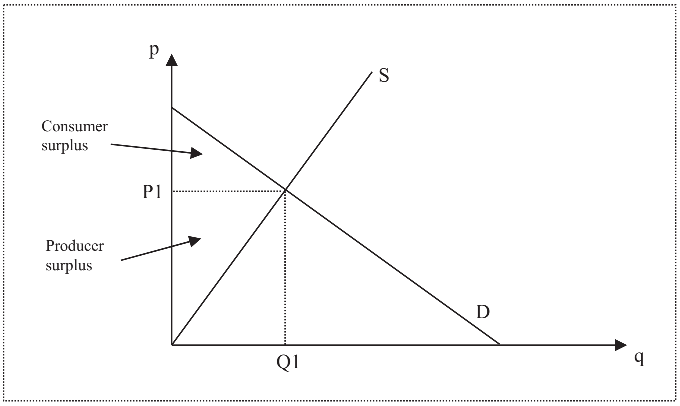

Fig. 1. The economic effects of a market exchange for farmers, consumers and society.

The supply function (S) is determined by the marginal costs of production. The total (variable) costs of quantity Q1 supplied to the market are given by the area below the supply function between the origin and Q1. As a matter of fact, total revenue by farmers is equal to total expenditure by consumers, i.e. the rectangle P1 * Q1. The triangle between market price and supply curve represents the economic value which accrues to the farmers through the market exchange (also called “producer surplus”). Total utility of society, or “social welfare”, can be calculated in this simplified approach by the sum of consumer and producer surplus.

The gain in social welfare, which arises from an increase in productivity, is shown in Fig. 2. An increase in productivity leads to falling production costs and, hence, to a shift of the supply function to the right, from S to S’. As a consequence, the equilibrium quantity increases to Q2, while the price falls to P2. Social welfare rises by the shaded area.

For the quantitative analysis in this paper, the social welfare effects have been derived with a multi-market partial equilibrium model. The model has been described in detail in von Witzke and Noleppa (2010) and Jechlitschka et al. (2007). The model covers the following regions: Germany, Rest of EU, North America, South America, Asia, Oceania, Rest of the World. The following commodities are included in the analysis: wheat, corn, coarse grains, rice, soybeans,

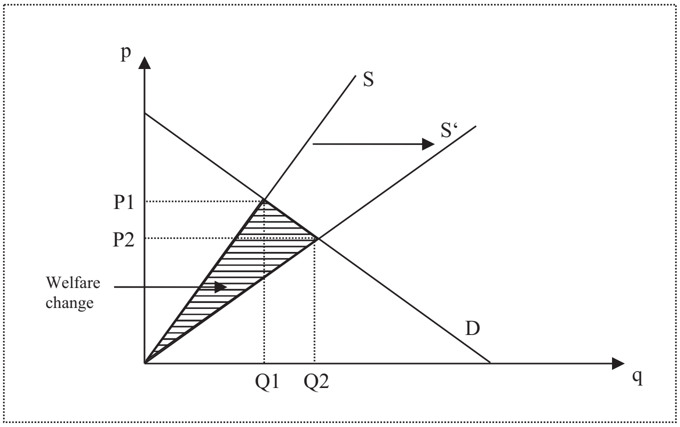

Fig. 2. The increase in utility for farmers, consumers and society, due to an increase in productivity.

palm fruits, other oilseeds, sugar crops, tropical beverages (coffee/cocoa/tea), fruits, vegetables, others.

Each domestic market in the model is described by iso-elastic supply and demand functions of the following general form:

$$q_i = a_i * p_i^{\varepsilon i} * p_j^{\varepsilon ij} \tag{2}$$

with q_i = quantity, a = constant term, p_i = own price, p_j = cross price (of all other commodities), ε_i = own-price elasticity, ε_{ij} = cross-price elasticity.

Changes in TFP enter the market model as shifts in the supply functions. Balance in world trade is achieved in the model by adding up net exports and net imports for each commodity across all regions. Consumer and producer surpluses are calculated as depicted in Fig. 1, based on supply and demand functions as described in Eq. (2).

If the social welfare gains in monetary terms, as derived from the market model, are compared to the economic resource use which has generated these welfare gains, we can use a standard concept for investment analysis to assess the social profitability of these investments. It has to be emphasized that this does not measure the private profitability of e.g. plant breeding enterprises nor of public research institutions. Instead, the social welfare gains of consumers and producers are counted as revenues of the investment, while monetary factor inputs are counted as expenditures of the investment. The net gain of society from investments in plant breeding or other types of agricultural research can then be calculated as follows:

Net welfare gain:

$$NW_t = W_t - WRP_t \tag{3}$$

Calculation of social rate of return:

$$\sum_{t=0}^{n} \frac{1}{(1+I)^t}(\Delta NW_t) = 0 \tag{4}$$

with: W = Social welfare gain (sum of consumer and producer surplus), WRP = Economic resource use for generating productivity increase through investments into plant breeding research, NW = Net welfare gain, t = Time index, I = Social rate of return of investments into research.

3. Data for calculation of productivity changes and agricultural research investments

Data on average yield changes and area changes for major agricultural crops have been taken from the FAOSTAT Statistical Database (FAO, 2010) (Appendix: Supplementary Table S1). Data for changes in factor input in German agriculture have been taken from statistics provided by the German Ministry of Food, Agriculture and Consumer Protection (BMELV, 2010). The "Economic accounts for agriculture" provide time series on changes in total agricultural labor use as well as total use of intermediate inputs (in volume terms at constant prices). While it would have been preferable to use crop-specific data on input use for this study, these numbers are only available for selected points in time, but not as time series. For the period 1990–2009, average labor input in German agriculture has declined by 2.5% per year, while intermediate input use has increased by 0.9% per year. Factor shares are only provided for the year 2000, at 20% for agricultural labor and 61% for intermediate inputs. Since area shares of the major crops have hardly changed in 1990–2009, the index of production can be approximated by changes in yields. If we combine changes in production with changes in labor use and intermediate input use (as in Eq. (1)), we can derive crop-specific changes in TFP for Germany (Fig. 3).

The derived rates of TFP change do not differ strongly from the rates of yield changes (Appendix: Supplementary Table S1). Hence, it can be concluded that observed increases in agricultural land productivity in Germany in the period 1990–2009 have been mainly caused by innovation, and only to a small share by increases in factor intensity.

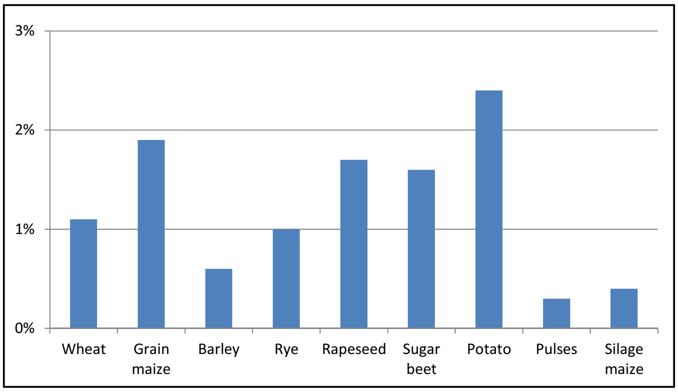

Fig. 3. Changes in total factor productivity (TFP) in German agriculture, 1990–2009 (in % per year).*Source:* Own calculations based on BMELV (2010) and FAO (2010).

Agricultural innovation can be caused by different processes, e.g. improved machinery, improved crop rotation and tillage, and also plant breeding. In the past, the share of plant breeding was estimated at around 50% (e.g. Duvick and Cassman, 1999; Reilly and Fuglie, 1998; Silvey, 1994; von Witzke et al., 2004). In recent years, the share has grown up to 90% of total TFP increase in some countries (Mackay et al., 2009; Webb, 2010). According to some German sources, the share of plant breeding in total TFP increase has also grown in Germany over time (Ahlemeyer and Friedt, 2010; Lege, 2010). In our analysis, we assume a contribution of plant breeding to TFP growth between 50% and 75%, which is a rather conservative range of estimates. Under these assumptions, yields for major crops in Germany in the period 1990–2009 would have been around 10–30% lower without the contribution of plant breeding (Appendix: Supplementary Table S2).

With regard to research investments in plant breeding, no official statistical data are available for Germany. Therefore, for this study primary data on research and development (R&D) investments were collected from private breeding enterprises in Germany. According to this unique set of primary data, R&D investments increased from about 103 million EUR in 1991 to about 119 million EUR in 2009. Suitable data on factor use in public breeding research institutes were not available. However, from the literature it is well known that in rich countries across the world public investments in agricultural R&D are approximately 50% of private investments. King et al. (2012) show this for the U.S., while Dietrich et al. (2014) use more general data sources for other parts of the world. For the following calculations we assumed that a ratio of 50% also holds for plant breeding research in Germany (Scenario "R&D investment low"). In an alternative scenario, the more conservative assumption was made that public investments in plant breeding research are at 75% of private investments (Scenario "R&D investment high"). Hence, total (public and private) research investments in 2009 amounted to 179 million EUR in scenario "R&D investment low" and 209 million EUR in "R&D investment high".

For calculating the additional CO_2 emissions from conversion of natural vegetation into agricultural uses, two suitable data sets were available (Searchinger and Heimlich, 2008; Searchinger et al., 2008; Tyner et al., 2010). Searchinger et al. derive on average higher emissions per hectare than Tyner et al. (2010) (Appendix: Supplementary Table S3). In our analysis we use the more conservative numbers from Tyner et al.

For the economic valuation of the emission savings the market price should be applied, if the price is the outcome of a functioning competitive market. Such a market does not exist. The price for CO_2 emissions is the result of an administratively generated market, where the price depends on the supplied amount of emission rights, and not on the costs of these emissions to society. In our ex-post analysis of saved CO_2 emissions, we use a price of 12.50 EUR/t CO_2, which was the average price for emission certificates in the European Emissions Trading Scheme in 2011. A more appropriate price for our analysis would be the so-called "shadow price", which is equivalent to the market price on well-functioning markets, which currently do not exist for CO_2 for the abovementioned reasons. The shadow price could be derived by quantifying the economic costs of CO_2 emissions. Currently available estimates of these cover a wide range. Ackerman and Stanton (2011) estimate that the true economic costs to society in 2010 are in a range of 28–893 US$/t CO_2. The German Federal Environmental Agency sets the social costs of carbon at 80 EUR/t CO_2. In any case, this would be significantly higher than a price of 12.50 EUR/t CO_2 which has been used here. Hence, the results of this study show the lower bound of the economic value of emission savings to society.

4. Results

4.1. Market effects of plant breeding research for consumers, farmers and society

Results of social welfare changes, based on pure market effects, are presented in Table 1. The total welfare gain from plant breeding research in Germany across all crops included in the analysis is in the range of 8.8–12.7 billion EUR for the period 1991–2010. Wheat accounted for the largest contribution, as wheat is the most important crop in Germany and the large harvested area works as a welfare multiplier for productivity growth. The contribution of pulses is very small, as harvested areas are small and little has been invested in plant breeding for these particular crops in recent decades.

Based on these welfare changes and two different estimates of the level of R&D investments (see Section 3), we are able to calculate social rates of return on these investments (Table 2). The pure market effects yield a social rate of return in the range of 20–40% per year.

4.2. Integrated market and climate effects of plant breeding research for consumers, farmers and society

In order to account for climate effects of investments into plant breeding research, we used our market model to calculate the additional area that would have had to be converted into agricultural use in 1991–2010, if there had been no technological progress in plant breeding in Germany (Table 3). The avoided area expansion in the period 1991–2010 worldwide is about 1–1.5 million ha. This is equivalent to about 8.5–12.5% of total cropland in Germany (Destatis, 2009). Improved varieties of wheat, rapeseed and barley have contributed the largest part to these area savings. Appendix: Supplementary Fig. S2 shows the distribution of potential area expansion across different world regions in our model.

If the avoided area expansion and the related savings in CO_2 emissions are valuated with appropriate prices (see Section 3), the economic value of the emission reductions through investments into German plant breeding research can be derived. Social welfare gains lie in a range of 2–2.9 billion EUR (Table 4). This is equivalent to about 160–235 million tons of CO_2 emissions.

Table 5 shows the resulting social rates of return, based on combined market and climate effects. The rates are between 40 and 80%

Table 1
Social welfare gain through German plant breeding research in 1991–2010 (accumulated, in million EUR).

	50% TFP through plant breeding	75% TFP through plant breeding
Wheat	3746	5503
Maize	700	1024
Barley	763	1114
Rye	278	412
Rapeseed	1411	2050
Sugar beet	1202	1738
Potato	2177	3103
Pulses	28	37
Total	**8787**	**12,724**

Source: Own calculations.

Table 2
Social rates of return on investments into plant-breeding research in Germany (market effects, ex-post 1991–2010, in % per year).

	50% TFP through plant breeding		75% TFP through plant breeding	
	R&D investment high	R&D investment low	R&D investment high	R&D investment low
Wheat	83	92	123	136
Maize	2	3	13	14
Barley	5	9	16	20
Rye	7	11	18	22
Rapeseed	10	15	20	26
Sugar beet	18	23	30	36
Potato	77	90	111	129
Pulses	n.a.	n.a.	n.a.	n.a.
Total	**21**	**25**	**33**	**39**

Source: Own calculations.

Table 3
Potential area expansion worldwide, without plant breeding research in Germany in the period 1991–2010 (in 1000 ha).

	50% TFP through plant breeding	75% TFP through plant breeding
Wheat	455	663
Maize	87	124
Barley	191	279
Rye	71	104
Rapeseed	259	373
Sugar beet	39	56
Potato	53	75
Pulses	4	6
Total	**1038**	**1507**

Source: Own calculations.

Table 4
Social welfare gains related to reduced CO_2 emissions through German plant breeding research in 1991–2010 (accumulated, in million EUR).

	50% TFP through plant breeding	75% TFP through plant breeding
Wheat	1217	1775
Maize	245	360
Barley	562	820
Rye	209	305
Rapeseed	663	957
Sugar beet	72	104
Potato	95	134
Pulses	12	17
Total	**2014**	**2931**

Source: Own calculations.

Table 5
Social rates of return on investments into plant-breeding research in Germany (Market and climate effects, ex-post 1991–2010, in % per year).

	50% TFP through plant breeding		75% TFP through plant breeding	
	R&D investment high	R&D investment low	R&D investment high	R&D investment low
Wheat	289	324	454	505
Maize	15	16	33	36
Barley	46	61	95	120
Rye	54	71	109	135
Rapeseed	35	49	69	93
Sugar beet	21	27	35	44
Potato	94	111	140	164
Pulses	n.a.	n.a.	n.a.	n.a.
Total	**39**	**48**	**68**	**83**

Source: Own calculations.

Table 6
Expected social rates of return on investments into plant-breeding research in Germany (Market effects, ex-ante 2011–2030, in % per year).

	50% TFP through plant breeding		75% TFP through plant breeding	
	R&D investment high	R&D investment low	R&D investment high	R&D investment low
Wheat	94	104	138	151
Maize	3	4	13	14
Barley	7	11	17	21
Rye	9	13	19	23
Rapeseed	18	23	29	35
Sugar beet	5	9	14	19
Potato	104	121	149	173
Pulses	n.a.	n.a.	n.a.	n.a.
Total	**25**	**29**	**38**	**44**

Source: Own calculations.

per year, i.e. about twice as high as for the market effects only (see Table 2).

Table 6 shows the results of an ex-ante analysis of the market effects, based on future market and price projections with the multi-market model. The social rates of return are on average higher than in the ex-post analysis, which is due to projected higher prices in the future. Higher prices boost the value of increased production caused by improved varieties from plant breeding. In this analysis we used rather moderate price projections by OECD (2011). Other projections provide higher results (FAO, 2009; Schwarz et al., 2011; von Witzke et al., 2009). The resulting effects in this study should be interpreted as a potential lower bound of the true effects.

Table 7
Expected social rates of return on investments into plant-breeding research in Germany (Market and climate effects, ex-ante 2011–2030, in % per year).

	50% TFP through plant breeding		75% TFP through plant breeding	
	R&D investment high	R&D investment low	R&D investment high	R&D investment low
Wheat	523	582	799	885
Maize	25	28	54	58
Barley	83	106	155	191
Rye	96	121	176	214
Rapeseed	103	136	176	226
Sugar beet	8	12	18	24
Potato	152	179	226	266
Pulses	n.a.	n.a.	n.a.	n.a.
Total	**64**	**80**	**112**	**138**

Source: Own calculations.

For the ex-ante analysis of combined market and climate effects for 2011–2030 we assumed an average CO_2-price of 25 EUR/t. This price reflects expectations that the economic value of CO_2 emission savings will rise in the future (e.g. Luderer et al., 2012), but is still below the lowest estimates for 2010 by Ackerman and Stanton (2011). Social rates of return on investments into plant breeding research in the future will be even higher than in the past, i.e. in the range of 65–140% per year (Table 7). This is partly due to higher agricultural prices in the future, and partly due to rising social costs of carbon emissions for society.

5. Discussion and conclusions

Global areas available for agricultural production are limited. Hence, increasing agricultural productivity plays a key role in providing more food and fighting hunger everywhere in the world (Schmitz et al., 2012). Moreover, rising land productivity reduces the expansion of agricultural land into tropical forests and the conversion of grassland into cropland. However, productivity increases do not fall like manna from heaven. They are the consequence of public and private investments into agricultural research (Dietrich et al., 2014). Based on a unique set of primary data and a combination of methods, this study has shown that agricultural research, and particularly plant breeding research, in Germany generates very high benefits from a societal point of view. The economic value of increased production generated through plant breeding research in Germany in the period 1991–2010 was in the range of 9–13 billion EUR. Moreover, an agricultural area expansion of 1–1.5 million ha worldwide has been avoided, which is equivalent to reducing 160–235 million tons of CO_2 emissions. The economic value of these avoided emissions for the German society was in the range of 2–3 billion EUR.

When the economic value of plant breeding research is compared to the economic resource use for generating the related productivity increases, a measure for the social rate of return on investments into breeding research can be generated. This rate of return is at 20–40% per year, when only the economic value of the increased production is taken into account. While these rates may appear rather high, they confirm earlier work (von Witzke et al., 2004). Moreover, our results are also in accordance with other analyses of the effects of public and private investments into agricultural research (Alston et al., 2000; Heisey et al., 2010; Pardey and Craig, 1989; Appendix: Supplementary Fig. S1).

The social rate of return rises to 40–80% per year, when also the social value of avoided CO_2 emissions is considered. This kind of combined analysis has not been done before. Moreover, the future social benefits of plant breeding research for the period 2011–2030 are reflected by a social rate of return at about 65–140% per year.

This indicates that public and private plant breeding research in Germany is extremely beneficial from a social perspective. However, it also indicates that, from society's perspective, there is an extreme under-investment in this area of research. Much higher levels of investment would be warranted in an activity with such high social rates of return.

Our results can be interpreted as a lower bound of the real effects, for at least three reasons. First, in each step of the analysis we made rather conservative assumptions, which are likely to lead to an underestimation of the individual effects (see Section 3). This applies to the contribution of plant breeding to total factor productivity increases as well as to the overall contribution of public breeding research, the avoided CO_2 emissions per area unit, and the CO_2 price. Second, employment effects which are generated by plant breeding along the agriculture and food production value chain have not been taken into account. Third, the contribution of plant breeding research to reducing hunger and malnutrition and the related loss of healthy and productive life years have not been analyzed.

Research has partly the character of a private good, but also a public good. Consequently, appropriate government activity is necessary to provide sufficient levels of investment into research. This applies, as could be shown here, also for investments into public and private agricultural research (Alston et al., 1995, 2009). For public agricultural research in Germany it can be concluded that severe budget cuts for agricultural research institutions at the federal and regional level, including agricultural universities, should be reversed. Lost research capacity should be expanded again to a level which reflects the true economic value of this knowledge-generating activity to society. This also applies to joint public–private research projects, which are frequently conducted in the case of plant breeding research. For private research, the political and institutional conditions for increased R&D investments have to be improved. For private plant breeding research in Germany, an appropriate protection and enforcement of intellectual property rights is of key importance.

It has to be emphasized that the EU has recently undertaken important and suitable reforms in the Common Agricultural Policy, which have brought agriculture closer to undistorted market conditions. Now, agricultural policy should also provide those public goods, which lay the grounds for fully exploiting the social benefits of agricultural production, for reducing hunger and reducing greenhouse gas emissions. Public and private agricultural research, including plant breeding research, has a key role to play in this.

Appendix: Supplementary material

Supplementary data to this article can be found online at doi:10.1016/j.agsy.2015.02.005.

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