The relation between water use and pesticides – Some remarks on the influence of integrated farming practices

Eva M. Noack[1], Holger Bergmann[2]

[1] Department of Agricultural Economics and Rural Development, Gottingen, Germany, e-mail: enoack@uni-goettingen.de
[2] Department of Agricultural Economics and Rural Development, Gottingen, Germany, e-mail: hbergmal@uni-goettingen.de

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Eva M. Noack*, Holger Bergmann**

* Department for Agricultural Economics & Rural Development, Göttingen, Germany, e-mail: enoack@uni-goettingen.de
** Department for Agricultural Economics & Rural Development, Göttingen, Germany, e-mail: hbergma1@uni-goettingen.de

Abstract *Agriculture is the main user of the world's water resources. Due to increasing concern on water quality and quantity, there is a growing interest to use the scarce water resources in the most efficient way to feed the growing world population. By employing a meta-analysis, this paper shows that pesticide use in combination with other improved production technologies have tripled agricultural water use efficiency (WUE) in the last 30 years. Recently, the European Union banned several active substances, among these more than 20 pesticides formerly used in crop growing. By doing so the progress in WUE has been put into question. This paper argues that a sudden reduction of pesticides by 50 % would lead to a need for more than 55 million hectares of additional arable land and for more than 158* km^3 *of additional water. Furthermore, in such a case the global irrigated area would have to be increased by 4 %. As most studies on the worldwide potential of additional arable land show, this land does not exist. Therefore, there are strong arguments to invest even further into new water saving technologies including pesticides. Specific research is needed to clarify which countries would be affected most by a sudden restriction or even ban of pesticides.*

Keywords: pesticides, water use efficiency, production technologies, food security

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Introduction

To feed the growing world population the production of food has to be increased (Carvalho 2006). In agriculture, two main measures to do so can be differentiated: intensification of already cultivated land and extension of arable land.

Of the world's land area, 30 % is potentially available for the production of wheat, maize, rice and soybeans; only 10 % are actually used (ibid.). Therefore, increasing arable land seems a viable option (FAO 2003). However, in contrast to this estimation, due to the multitude of already existing uses on these areas (e.g. grasslands, nature protection areas, forestry, renewable energy, etc.) there seems to be only a small proportion of land that can actually be converted into agriculturally used land.

Intensification seems – as all available statistics about yields show – to offer more potential. For example the worldwide average wheat yield is 2.6 tons per hectares (t/ha), while it is 3.3 t/ha in the developed world (FAO 2009). Worldwide wheat harvest could therefore be increased at least by 20 %. This intensification is however subject to the availability of capital, climatic restrictions, soil quality, and especially water availability (Rosegrant *et al*. 2002).

The particular importance of the factor "water" can be seen when considering that

- agriculture uses worldwide approx. 70 % of all used water (FAO 2003) and
- today approx. 40 % of harvested maize, rice and wheat is produced on the 16 % of irrigated arable land (Tilman *et al*. 2002).

Against the background of a growing world population (UN 2005), advancing climate change with increasing water scarcity (IPCC 2008) and water quality problems among others due to excessive pesticide (and fertiliser) use (Zwiener 1995), the question is how pesticides also contribute to a more efficient use of existing water resources. In this paper this question is first look at by assessing the consequences that a reduction of pesticide use would have on globally produced food resources. Then the respective effect on worldwide water use efficiency[2] (WUE; crop-water-productivity) is explored.

State of the art of the interaction of pesticides and water use efficiency

The relevant studies of the last 20 years have mainly analysed the interaction between pesticides and water quality (e.g. Pimentel *et al*. 1992, Pretty *et al*. 2000 or Leach & Mumford 2008).

Several authors have analysed the benefits and costs of pesticides, for example disputed in Germany: Waibel & Fleischer (1998); in the Anglo-Saxon literature most recently: Waibel & Fleischer (1998), Webster *et al*. (1999), Cooper & Dobson (2007) and Edwards-Jones (2008). All these studies have in common that they have overlooked the relation between pesticides and water use and water use efficiency, respectively.

Webster *et al*. (1999) show that without pesticides yield depression can reach 50 % and subsequently future profitability of farm enterprises would immediately be under question.

Following Cooper & Dobson (2007), 26 direct benefits and a number of indirect benefits of pesticide use can be found. Most important effects of pesticide use are the control of insects and weeds damaging agriculture and the control of human and animal diseases.

Based on the existing literature, other external effects of pesticide use have found broad interest while the interactions between pesticides and water use have mostly been neglected (e.g. Pimentel *et al*. 1992, Pretty *et al*. 2000). However, it should be mentioned that the production potential in relation to pesticides has not been exploited yet and that use of more pesticides might be advisable (Lansink & Silva 2004).

In general, there is a positive relation between nitrogen fertilisation and water use efficiency (e.g. Brueck 2008 or Viets 1962). As Zhang and Oweis (1999) show there is also a positive linear relation between available water quantity and yield potential for wheat.

Brueck *et al*. (2000) show for phosphorus that dependent on water availability a positive effect (more efficient water use if water is abundant) or a negative relation can be observed (less efficient water use if water is scarce) (cf. also Morgan 2003 or Mussavi *et al*. 2009). Therefore, it can be assumed that there is no general positive linear relation between phosphorus and pesticides use and yields.

If used appropriately fertiliser and pesticide use show positive correlation with wheat yields (Mussavi *et al*. 2009). Especially the relation between nitrogen and WUE is positive (Hussain & Al-Jaloud 1995). As simultaneously pesticide use and nitrogen use are positively related, the assumption that there is also a positive relation between pesticide and water use (and its efficiency) is supported by literature. However,

[2] Water use efficiency (WUE) is defined as the ratio of economical yield to total water use or total evapotranspiration (Copeland *et al*. 1993).

it has to be mentioned that Petty *et al*. (2006) show that to some extent pesticides can reduce WUE as well as yields in some cultures, especially if their use is too high.

Oleson *et al*. (2000) show for wheat in Denmark that fungicide use is positively related to the nitrogen quantity used. As nitrogen fertilisation is strongly positively correlated with better WUE, it can be assumed that appropriate fungicide use can significantly reduce the relative water use per yield unit.

For wheat Szumigalski & Van Acker (2008) show that an influence of herbicides on WUE cannot be assumed. However, this new result stands in sharp contrast to the findings of Daniels and Scott (1991), who find a generally positive influence of herbicides on yields as well as on WUE.

Duan *et al*. (2008) find that under water stress growth regulators can increase wheat yields by a maximum of 22 %. In case of adequate water supply these regulators can even increase yields by up to 25 %.

Borza (2008) demonstrate that an abdication of herbicides in maize can decrease the WUE between 44 % and 79 % in irrigated and between 42 % and 89 % in rain fed farming.

Haq *et al*. (2002) show that appropriate use of herbicides and fungicides in combination with irrigation increases yields by 10 % to 15 %.

Bhagat *et al*. (1999) declare for rice that higher application rates of pesticides provoke higher yields and subsequently higher WUE. Apart from this, the authors report that in experiments without herbicides significantly lower WUE as well as yields have been measured.

Based on the reviewed literature on the interaction between pesticides and WUE the following conclusions can be drawn:

1. Herbicides increase the WUE.
2. Growth regulators increase WUE if water is scarce.
3. Fungicides increase WUE indirectly and have a positive effect on the product quality.
4. Effects of insecticides on WUE have not yet been analysed in literature.

With reference to rain fed farming, it can be concluded that

1. pesticides increase WUE only to a small extent,
2. artificial fertilisers in combination with pesticides and new plant varieties (maize, soy beans, wheat and rice) increase yields proved for the developed world and
3. appropriate pesticide use can save water resources.

Referring to irrigated cultivation, the following can be found:

1. Pesticides have a positive significant influence on WUE.
2. Herbicides in combination with bio-technological engineered varieties and appropriate plant production systems increase yields significantly.
3. Application of pesticides can increase WUE to up to 25 %, i.e. water resources can be used significantly more efficient when pesticides are applied.

Effects of a reduction of global pesticide use on water use

World population (2008) annually demands between 620 and 650 million tons of wheat[3], between 700 and 750 million tons of maize and between 400 and 440 million tons of rice. The cultivation of these three most important food plants requires some 530 million hectares (ha) at the moment, which is more than 10 % of arable land available worldwide. The land in maize and wheat is mainly found in rain fed regions and rice production in areas with irrigation.

[3] See http://www.igc.org.uk/en/grainsupdate/igcsd.aspx and http://www.agrarheute.com/?redid=19060 (both accessed on 08.04.2010) and USDA (2008).

Table 1: Harvested area, average yields and world production of maize, rice and wheat in 2005

	Harvested area (in million hectare)	Yield (in tons per hectare)	World yields (in million tons)
Maize	147.8	4.8	715.8
Rice	154.7	4.1	631.9
Wheat	220.2	2.8	626.5

Source: USDA 2008

Knutson (1999) shows that a ban of pesticides in the USA would lead to yield depression in maize of up to 32 %, in wheat of up to 24 % and in rice of up to 57 %. A ban of herbicides alone would result in yield depressions in maize of 30 %, in wheat of 23 % and in rice of up to 53 %. The effect of a combined fungicide and insecticide ban would be a yield reduction of 5 % in maize, 4 % in wheat and probably up to 16 % in rice (ibid.). Overall this yield depression would be accompanied by a significant depression in WUE as well as by smaller decreases in absolute water use. It can thus be assumed that a worldwide ban of pesticides would result in significant yield depressions in Europe as well as in the Americas accordingly.[4]

Tentative calculations based on the above presented review suggest that due to higher yields and yield potentials in the European Union[5] yields would decrease by 32 % (maize), 24 % (wheat) and 57 % (rice). As yield potentials (and yields) of rice are generally smaller in South-East Asia, smaller yield depressions than in the USA have been assumed (half of the level according to Huang *et al*. 2002).

The following calculations were done for a medium scenario, assuming a ban of only half of the pesticides and a yield depression of only 50 % of the yield depression that would result from a total ban of pesticides (most extreme scenario).

Table 2: Assumptions of yield depression in percent and arable and irrigated land in million hectares per region

Crop losses (in percent)	Maize	Wheat	Rice	Harvested area (in million hectare)	Irrigation area (in million hectare resp. percent)	
Africa	0	0	0	213,119	13,496	6 %
Americas	16	12	23	365,060	41,810	11 %
Asia	0	5	12	511,459	195,480	38 %
Europe	16	12	23	280,073	26,615	10 %
Oceania	0	12	5	51,458	2,974	6 %

Source: Own estimation and FAOSTAT

[4] These calculations are based on literature for extreme scenarios. For the following calculations a much more conservative approach has been chosen. Whether these assumptions and the results are right can only be decided in further studies.

[5] If not stated otherwise, we refer to the EU-27, i.e. Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxemburg, Malta, the Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden and the United Kingdom.

For the calculations it was then assumed that each world region will first try to produce the same amount of food as in 2005 if yields decrease due to a partial ban of pesticides. International trade as a source of additional food is excluded (ceteris paribus condition).[6]
This means that the area for maize, wheat and rice would have to be increased in each region. Simultaneously, it has to be realised that in the classical irrigation areas in North Africa and South-East Asia more than 80 % of the potentially arable land is already used. Therefore, as the FAO remarks, there is hardly any more area that could be activated for farming.
This means that in case the water supply stays the same for wheat, maize and rice the planted area in the USA and the EU-27 would have to be increased by between 15 % and 25 % (FAO 2003, USDA 2008).[7]
Concurrently, WUE would be reduced by between 10 % and 20 % and some additional water between 10 % and 20 % of today's water use would be needed especially in irrigation farming in Asia, Americas and Europe. Whether this amount of water is likely to be available, especially in particular if one considers climate change and often occurring droughts, cannot be answered for sure (IPCC 2008).
In order to calculate the additional water use for the case of a partial pesticides ban, some standard figures concerning crop water productivity are needed (see Table 3).
Depending on the intensity of the production system up to 1.7 kg of wheat, between 2.7 kg and 2.9 kg of maize and about 1.6 kg of rice can be produced per cubic metre (m^3) of water (see Table 3).[8] As table 3 shows, remarkable progress in terms of crop water productivity (CWP)[9] has been achieved since the late 1970s.
In line with the precedent findings it is assumed that if pesticide use is reduced by 50 % WUE will decrease by 0.25 kg in wheat, 0.375 kg in maize and 0.25 kg in rice per cubic metre of water (Zwart & Bastiaanssen 2004). Therefore, the global water demand would increase by 64 km^3 in wheat, 37 km^3 in maize and 57 km^3 in rice (see Table 7 in the appendix).

Table 3: Crop Water Productivity (kg/m^3)

Crop	following Doorenbois & Kassam		Zwart & Bastiaanssen	
	Min.	Max.	Min.	max
Wheat	0.8	1	0.6	1.7
Maize	0.8	1.6	1.1	2.7
Rice	0.7	1.1	0.6	1.6

Source: Doorenbos & Kassam (1979) and Zwart & Bastiaanssen (2004)

If pesticides are banned or allowed use is reduced 55 million hectares of arable land would have to be activated which equals 5 % of today's cultivated arable land (see Table 4 to 6 in the appendix) (FAO 2009). Regarding this activation however, it has to be differentiated between rain fed and irrigation cropping. While in the regions of rain fed farming there is no activation potential (cf. ibid.), it might be possible to increase the irrigated area in the developing world, and probably in the least developed countries (FAO 2003). While this possibility is limited in China, South Asia and in Northern Africa because more than 80 % of all cultivated land is already irrigated, there might be some potential in South America and in the rest of Africa. As the calculations in Table 8 show it would be expected that irrigation areas would increase worldwide by 5.1 %. More specific, in Asia it would increase by 4.7 %, in Europe

[6] In general, an alternative approach would be to assume that in regions that would be affected most by a ban of pesticides could not increase their arable land and that therefore those regions with smaller yields at the moment would in the first place to produce the missing quantities of food. These regions would basically be South America, Africa and Asia.
[7] see Table 4, Table 5 and Table 6
[8] One m^3 of water equals 1,000 litres.
[9] Crop water productivity (reciprocal of WUE) is defined as crop yield per water consumptively used in evapotranspiration (Kassam & Smith). It may be quantified in terms of amount of yield (wet or dry), nutritional or economic value.

by 3.9 % and in Oceania by 3.5 %. Overall, the irrigated area would have to be increased by 12.4 million ha.
As the FAO estimates show an increase of WUE is hardly to be expected in these regions (e.g. Faurèsa *et al*. 2003) and therefore up to 290 km^3 of additional water might be needed worldwide to sustain the current levels of production.[10] Such needs will mostly be expected, as the FAO (2003) shows, in countries that have concentrated on irrigation farming.
As said beforehand the potential for new arable land is restricted as
(a) on the new land yield potentials are low because of sparse water and soil nutrients,
(b) in many developing countries bad infrastructure prevails (cf. Azar & Larson 2000),
(c) the already efficient allocation of land resources on forestry, grasslands and other land use demands.
As the UN (2005) as well as the FAO (2003) show, potential arable land can be found mostly in areas that already need to be protected for nature conservation, environmental reasons (erosion, degradation, and salinisation) or which are simply not suitable for food production.
Adding to this argument, Tilman *et al*. (2002) show that even in the so called „early adopter regions" of China, South Korea and Japan maximum yields as well as maximum land use are already reached at present.

Conclusion

Agriculture is the biggest user of water resources worldwide (FAO 2003). The growing world population can only be fed by an appropriate combination of pesticides, new plant varieties, fertilisers and new production. Pesticides have tripled the WUE in the last 30 years in combination with other production technologies (ibid.). In irrigation cropping these methods have lead to increases and a rising WUE (Faurèsa *et al*. 2003). A sudden reduction of pesticides by 50 % would lead to an additional need for more than 55 million hectares of arable land, which would subsequently lead to a demand of more than additional 158 km^3 water.[11] Furthermore, it could be expected that in such case the globally irrigated area would have to be increased by 4 %. Such increases seem to be possible but not very likely as the water resources are available especially in Europe as well as in Northern America, but not in other parts of the world. However, wider economic consequences – that so far have been excluded from the analysis – have to be considered if one really is tempted to reduce pesticide use significantly. Obviously, with increasing food demand as well as decreasing amounts of available arable land, such a ban would further increase hunger worldwide. The effects of such a measure on commodity prices might – as the price bubble of 2007/8 have shown – be quite significant and lead to food scarcity across the developing world. As the impacts of higher commodity prices have shown, the follow-up effects of lower yields might lead to lower worldwide stocks, much higher price fluctuations and quite surely public unrest in developing and developed countries. This might lead to new protectionist policies across the world. Whether these political implications can be tolerated in a globalised world in which not only traded goods but also information as well as people cross borders, is an open question.
Further research needs to clarify which interaction exists between yield depression and water use if pesticides are banned. Furthermore, the regional as well as national effects of such a scenario for all countries have to be estimated to come to better estimates. Through meta-analysis the question which relations exist between water use efficiency and

(a) herbicides,
(b) growth regulators,
(c) fungicides, and
(d) insecticides

should be further explored.

[10] In comparison, the actual water use in 1999 was 2,100 km^3.
[11] See Table 7 in the appendix, last row: 64 km^3 for wheat, 37 km^3 for maize and 57 km^3 for rice.

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Appendix

Table 4: Maize assumption 30 % yield depression in developed countries for 2005.

Maize	Harvested area in million ha 2005	Harvested area in million ha calculated	Change in percent	Yield in t/ha 2005	Yield in t/ha Calculated	Change in percent
Africa	28.8	28.8	0 %	1.8	1.8	0 %
Americas	57.9	68.9	-16 %	6.6	5.5	19 %
Asia	47.2	47.2	0 %	4.2	4.2	0 %
Europe	13.8	16.4	-16 %	6.2	5.2	19 %
Oceania	0.1	0.1	0 %	6.7	6.7	0 %
Total	**147.8**	**161.4**	**-8 %**	**4.8**	**4.4**	**9 %**

Source: USDA 2008 and own results

Table 5: Wheat assumption 12 % yield depression in developed countries resp. Asia 5 % for 2005.

Wheat	Harvested area in million ha 2005	Harvested area in million ha Calculated	Change in percent	Yield in t/ha 2005	Yield in t/ha Calculated	Change in percent
Africa	10.0	10.0	0 %	2.1	2.1	0 %
Americas	38.8	44.1	-12 %	2.7	2.4	14 %
Asia	98.8	104.0	-5 %	2.7	2.6	5 %
Europe	59.6	67.7	-12 %	3.5	3.1	14 %
Oceania	13.0	14.8	-12 %	2.0	1.7	14 %
Total	**220.2**	**240.6**	**-8 %**	**2.8**	**2.6**	**9 %**

Source: USDA 2008 and own results

Table 6: Rice assumption 23 % yield depression in Developed Countries, China and Oceania minus 12 resp. 5 %

Rice	Harvested area in million ha 2005	in million ha Calculated	Change in percent	Yield in t/ha 2005	in t/ha Calculated	Change in percent
Africa	8.8	8.8	0 %	2.3	2.3	0 %
Americas	8.1	10.5	+23 %	4.5	3.5	-30 %
Asia	137.2	155.9	+12 %	4.2	3.7	-14 %
Europe	0.6	0.7	+23 %	5.8	4.5	-30 %
Oceania	0.1	0.1	+5 %	0.0	0.0	0 %
Total	**154.7**	**176.0**	**+12 %**	**4.1**	**3.6**	**-14 %**

Source: USDA 2008 and own results

Table 7: Estimated actual and additional worldwide water use in wheat, maize and rice through reduced pesticide use (-50 %)

	Wheat	Maize	Rice
Yield in million tons	716	627	632
CWP in kg/m^3	1.8	2.7	1.8
Water use in km^3	398	232	351
CWP Loss in kg/m^3	0.25	0.38	0.25
CWP New in kg/m^3	1.6	2.3	1.6
Water use (Scenario) in km^3	462	269	408
Additionally needed water in km^3	64	37	57

Source: Own estimation

Table 8: Change in irrigated area through pesticide reduction

	Arable land in million ha	Irrigation technology fit area in million ha	Irrigated area in percent	Potential arable area in million ha	Add. irrigation area in million ha	Change irrigation area in percent
World	1421.17	280.38	20 %	55.4	12.4	4.4 %
Africa	213.12	13.50	6 %	0.0	0.0	0.0 %
Americas	365.06	41.81	11 %	18.7	2.1	5.1 %
Asia	511.46	195.48	38 %	23.9	9.1	4.7 %
Europe	280.07	26.61	10 %	10.9	1.0	3.9 %
Oceania	51.46	2.97	6 %	1.8	0.1	3.5 %

Source: Own calculations