PESTICIDE USE: CROP MANAGEMENT, YIELD AND ENVIRONMENTAL IMPACT ON POTATO FIELDS IN THE NETHERLANDS

MSc. Thesis Plant Production Systems

(Image: Pauline Eccles, 2011)

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ABSTRACT

The use of pesticides in agriculture is often seen as a negative aspect in food production. Nevertheless, their use aims to avoid yield and economic losses. The high amount of pesticides used for production in the Netherlands before the 1980's captured the attention of scientists and policy makers. Several measures were taken to reduce the dependence on pesticides in agricultural production. Still, the effects of pesticide use need to be continuously monitored and evaluated. Using a database with information on crop fields, yield and spraying operations, provided by AgroVision B.V. (*Cropmanagement*); we evaluated the relation between pesticide use yield, environmental impact and biophysical conditions applying Linear Mixed Models (LMM), Stochastic Frontier Analysis (SFA) and Boundary Line (BL).

Yield was c.a. 8% lower in 2016 compared to 2017 and 2015. Seed potato yield was c.a. 14 ton/ha lower than ware (50.9 ton/ha) and starch potato (49.1 ton/ha). Seed potato showed less pesticide sprayings (13) than ware (16) and starch potato (17); and a lower pesticide input with 10 kg of active ingredient (AI) per hectare compared to ware (11.5 kgAI/ha) and starch (12.7 kgAI/ha). Years 2016 and 2017 presented a higher AI input (12 AI kg/ha) compared to 2015 (10.8 AI kg /ha). Ware and starch potato varieties Hansa and Festien showed the highest AI input compared to Melody (10kgAI/ha) and Seresta (12. kgAI/ha); variety Fontane showed higher AI input (c.a.10kgAI/ha), than Innovator and Spunta (c.a. 9 AI kg/ha) in seed potato. Concerning regions AI input related to N Coast was the lowest (8.7 AI kg/ha), while South accounted for the highest input (14.1AI kg/ha).

The environmental impact points (EIP) were 20% higher in 2016 compared to 2015 and 7% higher compared to 2017. Ware and starch potato accounted for the highest EIP values, (c.a. 3000 EIP); while seed potato showed the lowest (2561 EIP). Soil life is the most affected by pesticide use in the three potato crop types; aquatic life was mostly affected by ware potato production and ground water was mostly affected by starch potato. Fungicides accounted for the highest share in the total AI input; around 70% in seed and ware potato and ~80% in starch potato. Almost a third of the EIP were related to insecticides despite its low contribution to total AI (3%), which shows its high environmental burden.

Fungicides affected yield positively in a small extent, the effect was consistent in all crop types with c.a. 0.07 ton/ha in ware and starch potato, and 0.10 ton/ha in seed potato. A negative influence on yield in 2016 was found significant in ware and starch potato (c.a.-0.10). The effect of the interaction fungicide x insecticides on yield was found positive in starch potato, but negative in seed potato; while the interaction between herbicide x insecticide positively affected yield in ware potato. The interaction between insecticide and sandy soil positively affected yield in ware and starch potato.

Yield plateau showed an AI input of ~ 5kg AI/ ha. Narrow differences were found between AI amount in starch potato for different yield levels. Low yielding fields coincide with low EIP and AI in ware in starch potato. Minimum thresholds of EIP per unit of AI are similar in ware, starch and seed potato from 100-140 EIP. Nevertheless, upper thresholds vary among crop types suggesting that pesticide combinations in ware potato (1300 EIP) have a higher environmental impact than seed (130 EIP) and starch potato (326 EIP). A wide range of EIP values were found for a given AI input level, this suggests that pesticide pollution characteristics play an important role in the environmental impact of the fields.

We concluded that a) yield, AI input, and environmental impact are strongly influenced by the type of potato produced, b) low amounts of AI input does not necessarily imply less environmental impact, c) the relation between AI input and yield is limited and d) the wide range of AI and EIP for a given yield suggest that shift from average yield to high yield could be done without increasing the environmental impact.

Key words: Pesticide use, potato production, active ingredient, environmental impact.

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1. INTRODUCTION

1.1. USE OF PESTICIDES IN AGRICULTURE

The use of pesticides for crop protection has played an important and controversial role in world agriculture. Its function in the prevention and control of harmful organisms during plant production and storage has contributed to reduce yield loss, preserve post-harvest quality, and indirectly reduce food prices.

According to the Environment Protection Agency (EPA), the world expenditure on biocides in crop production was $56 billion USD in 2012. In total, 394 701 kilograms of Active Ingredient (AI) were sold among the 28 countries of the European Union in 2014. Among these products, insecticides, fungicides, and herbicides account for the largest proportion of the world pesticide expenditure between 2008 and 2012 (EPA, 2017). There is a similar trend in the European Union, where insecticides, acaricides, fungicides, and herbicides represented the major proportion in pesticide sales in 2012 (EUROSTAT, 2017).

Despite the benefits of using pesticides for crop protection, the ample variety of pesticide properties and control targets represent a potential hazard for the environment, biodiversity, and food safety (Marrs et Ballantyne, 2004). The contamination of food for human and animal consumption, the exposure of operators and workers, the translocation of active ingredients to different environmental components, the impact on non-target organisms and the development of resistance by accelerating the selection processes are some or the potential risks associated with pesticide use (Pathak et al. 2001).

After the concern created in the late 1960's about the use of pesticides in agricultural production, several efforts have been made to improve the management practices in pesticide use (Epstein, 2014). However, best management practices must be constantly monitored and combined with upcoming technologies in the sector.

1.2. USE OF PESTICIDES IN THE NETHERLANDS

In 1991, the Netherlands accounted for the highest amount of pesticide applied per hectare among European countries (20.8 kg of AI), compared to Belgium (12.2 kg), France (6.0 kg) and UK (5.8 kg) (Oskam et al.,1992). This was attributed to 1) climatic conditions that favoured the development of fungal and bacterial diseases, 2) intensive farming with narrow rotations that favoured soil borne diseases, 3) as a measure to reduce yield loss and potential economic loss and, 3) to comply with sanitary regulations for international trade to avoid the propagation of pest and diseases (Oskam et al.,1992).

The implementation of the long-term crop protection plan (MPG-J, 1991, revised by Oskam et al., 1992) aimed to reduce pesticide use, limit pesticide emission and reduce farmer's dependence on pesticides. The plan relied on the close involvement of the Dutch government through policy instruments that enhanced the adoption of new management practices in crop protection. By 2010 the Netherlands managed to reduce pesticide use from 20,268 tonnes of active ingredient (AI) in 1990 to 9,182 tonnes in 2010 (-54.7%). The reduction of soil disinfection products, represented a 44% (8938 ton) of the reduction in total consumption in 1990 (Peshin et Zhang, 2014).

In 2006, the average amount of AI applied per hectare of arable land was 6.6 kg (CBS, 2006). However, the amount of pesticide AI remained prominent for high valued crops such as onion (10 kg/ha) and potato (20 kg/ha) (LEI, 2011). The agricultural economic report, the average amount of active ingredient (AI) applied per hectare of arable land was 6.6 kg. However, the amount of pesticide AI remained prominent for high valued crops, such as onion (10kg) and potato (20kg) (LEI, 2011).The Agricultural economic report (LEI, 2015) informed that the sales of crop protection products fluctuated between 9.9 and 10 million kilograms of AI, of which 98% is destined to the agricultural sector.

1.3. YIELD LOSS, CROP PROTECTION AND DECISION MAKING

Crop yield losses due to weeds, pest and diseases are considered as growth reducing factors that hamper the achievement of the potential yield (van Ittersum et al., 2013). According to the study performed by Oerke (2006) the potential yield loss is 75% from attainable yield without control for these reducing factors. The actual yield losses in potato varied from 24% in Northwest Europe to 50% in Central Africa. In general, losses despite crop protection practices in potato, are estimated at 7, 8, 11 and 14% due to viruses, weeds, animal pests and pathogens, respectively (Oerke, 2006).

Data collected for the European Food Security Authority (Garthwaite et al., 2015), to assess worker's and operator's exposure to pesticides, provide a glimpse of the type and frequency of pesticides used in crop production in the Netherlands. The farms under study where located in Flevoland and Noord Brabant, considered as the major areas for potato and other vegetable crops. The study showed that on average 19 spraying rounds were done during the growing season and 36 different AI were used (Garthwaite et al., 2015)

The fact that several types of diseases threaten potato production may lead to higher use of pesticides compared to other crops to preserve yield and quality (Askew, 2006). In the Netherlands, potato late blight (*Phytophthora infestans*) is the most important disease affecting the potato crop. This pathogen is favoured by wet weather conditions, the increase in potato hectarage and the outbreak of *P. infestans* resistant strains to commonly used pesticides like metalaxyl (CABI, 2017; Zwankhuizen & Zadoks, 2002).The average cost of chemical control and spraying of late blight in potato is 330 €/ha per season, which sums up to 115.5 M€ nationally (Haverkort et al., 2008).

Pests, weeds and diseases can affect yield and food quality directly and indirectly through economic losses (i.e. farmers income, market supply). However, the relation between disease injuries and yield loss is rather complex, as well as the prediction of economic losses, which are dependent on the socioeconomic context. This raises uncertainty in decisions concerning crop protection management (Savary et al., 2012). The management of pest and diseases at farm level can be strongly related with farmer's assets and perceptions. Therefore, decisions on crop protection can be made upon the comparison between the potential loss in terms of income that crop damage represents and the costs of the options to supress pests and diseases (Oerke, 2006).

According to the study performed by Lechenet et al., (2017), farms growing industrial crops with high yield potential, such as potatoes, come along with the highest values in profitability, as well as higher values for Treatment Frequency Index (TFI), which is an indicator for the intensity in pesticide use defined as the ratio between the applied amount of AI per hectare and the recommended amount per hectare. Oerke (2006) suggests that the high added value of these crops may influence farmers' decision on crop protection management practices since preventing losses from high added value crops can be more profitable than investing in the crop protection of low revenue crops.

1.4. PESTICIDE USE AND ENVIRONMENTAL IMPACT

The assessment of the environmental implications of pesticides has continuously been under study to improve crop management practices. Pesticide application has diverse effects beyond plant protection on a specific plot. The most common sources of pollution are the spray drift, pesticide leaching and atmospheric deposition (van Eerdt et al., 2010). The drift during pesticide application can reach non-target plants and organisms and surface water through run off (Aktar et al., 2009). Furthermore, pesticides can either reach ground water through leaching or remain in the soil, depending on the type of molecules and their interaction with soil particles ultimately posing potential threats to non-targeted soil organisms (Del Prado-Lu, 2015).

According to Geiger et al. (2010), in west and east European countries, including the Netherlands, the use of pesticides has a strong negative effect on the diversity of carabids, wild plants, potential natural enemies for pest control and ground nesting farm-land birds whose biodiversity declined with the increase in application frequency. An overview given by Schipper et al. (2008) about the situation of groundwater and drinking water in the Netherlands showed that 24% of 771 samples taken, pesticide residues were found in ground water bodies and 11% exceeded the limit (1µg/l) set by the Water Framework Directive (WFD).The impact of pesticides on the environment, workers and final consumers led to the need of developing environmental impact indicators to quantify associated effects and reduce risks. The methodology and assessment of these indicators differ depending on the purpose on the indicator (Reus et al., 2002).

In 2015, countries in the United Nations adopted the "2030 agenda for sustainable development". This agenda comprises a set of 17 sustainable development goals (SDG's) to end poverty, ensure wellbeing and protect the planet (UN, 2015). In this context, the project Towards Sustainable and Resilient Agriculture(TSARA) aims to develop pathways to achieve the UN SDG's and common targets in Dutch agriculture. Gil et al. (2017) reviewed and assessed SDG -2 indicators, 5 of these indicators required priority for reaching SDG-2 targets: pesticide use, N surplus, N use efficiency, GHG emissions, intensity and genetic diversity. For this 5 indicators, targets and pathways need to be defined. Pesticide use can be can be compared at global level, using global database, using the indicator pesticide applied/area (1000ton/ha) (Gil et al., 2017). However, at national level there is much more information available on the environmental impact of pesticides, that can be used more precisely to set targets in pesticide reduction than global databases.

The present research aims to provide further information on pesticide use in potato production systems in the Netherlands. This study provides first a general overview of pesticide use in potato given the characteristic of the different purposes of this crop and how it relates with crop management; followed by the environmental impact of pesticide treatments on potato fields; and finally, its relationship with yield and possible reductions.

1.5. OBJECTIVE AND RESEARCH QUESTIONS

The main objective of this research is to:

Analyse the relation between the amount of pesticide use and the (i) impact on the environment and (ii) crop yield across different potato production systems in the Netherlands.

To achieve the objective of this study, the following research questions will be assessed:

1. How does pesticide input (AI kg/ha) vary according to biophysical conditions and crop management?

2. How does pesticide use affect the environmental performance of potato production systems?

3. What is the relation between yield, the amount of active ingredient applied, and the environmental impact of the pesticides used?

2. MATERIALS AND METHODS

2.1. DATABASE: GENERAL DESCRIPTION

The database used for this research contained information on crop management on potato fields, distributed across the Netherlands (Table 1). This information was entered by farmers during the growing seasons 2015, 2016 and 2017. The data was collected through the crop management software Crop Central (AgroVision B.V.).

2.1.1. Crop Fields

The fields are related to a specific farm. Every farm and field are interlinked by a unique identification number (Farm ID, Crop Field ID). The size of the fields has and average range of 3-6 ha. The information on the soil type is given for each field, according to the Dutch soil classification system (Steur,1985: discussed by Hartemink et al., 2013). The database also contains information on the location of crop fields in decimal coordinates (EPSG:4326) and/ or postal codes.

2.1.2. Crops and management

In the database potato crops are classified in three types: ware potato (Crop ID 1), starch potato (Crop ID 2), and seed potato (Crop ID 3). The potato variety cultivated on each crop field is also specified. The yield obtained at harvest is recorded as Fresh Weight (FW) per unit of area. Crop management operations performed on each field are recorded such as fertiliser application, irrigation, pesticide applications and harvest. The dataset also provides information about the date when the operation was performed. For this research, only the operations related to pesticide sprayings and harvesting were considered.

2.1.3. Pesticide information

The database comprised information on the pesticide type applied (fungicides, herbicides, insecticides, algicides, nematicides, molluscicides). Pesticide description included the commercial name of the product, active ingredient and the dosage applied. Environmental Impact Points (EIP) for each pesticide product were also available on the database Impact scores from the Environmental Yardstick on aquatic life, soil life and groundwater were considered for the EIP calculations for the aim of this study (detailed information in section 2.3.1).

Table 1. Summary of variables related to field characteristics, crop management and pesticide use.

Type	Variables	Units	Source
Field	CropYear	2015-2017	Database
	Farm ID	-	Database
	CropField ID	-	Database
	Field location	Decimal coordinates (EPSG:4326)	Database
	Field Size	ha	Database
	Soil Type	-	Database
	Soil Organic Matter	%	SOM map (Alterra) (Berg et al., 2017)
Crop	Crop type	Ware, starch, seed potato	Database
	Variety	-	Database
	Yield	ton/ha	Database
	Operation name	-	Database
	Date	dd/mm/yyyy	Database
Pesticide	Pesticide type	-	Database
	Active ingredient	kg/l or kg/kg	Database
	Dosage	kg/ha or l/ha	Database
	EIP scores per product	EIP	Database
	Count of sprayings	number	Calculated
	Total Active Ingredient	AI kg/ha	Calculated
	Total EIP	EIP/ha	Calculated

2.2. DATA SELECTION

2.2.1. Crop Fields selection

The information was selected and organized through queries built in Microsoft Access 2016. Crop fields with non-duplicated management operations were selected. The queries were done per year under the following criteria:

1. Crop types: ware, starch, and seed potato
2. Fields with only one harvest operation registered.
3. Fields with registered yield between 10 and 150000 kg/ha. Values registered with a different unit (e.g. ton/ha) were also included.
4. Operations related to the application of plant growth regulators after harvest were excluded since the dosage for the application of these products was unknown.
5. Seeding and planting operations were excluded for the following reasons:

   a) Pesticide applications that were unlikely to happen at the same time of planting/seeding were registered, such as herbicide applications.
   b) If more than one variety was reported on the same field at planting, each pesticide application performed on the field would be multiplied times the number of varieties registered.
   c) The information of pesticide application at planting did not specify if the treatment was sprayed on the field or applied directly to the seed tuber (i.e. seed treatment).

The data was extracted from the database using queries built in Microsoft Access. The information between the different tables of the database was linked through unique identity numbers: Farm ID, Crop field ID, Crop ID, Operation ID, Product type ID. The data of the selected fields was organized using the “Group by” function. Operations performed on the crop fields were ordered by date, from oldest to the newest.

2.2.2. Data management

2.2.2.1. Yield

The data management was done using Microsoft Excel (2016) and Rx64 (version 3.4.3) using the RStudio integrated development environment (IDE). Crop yield was standardized to ton/ha. After the standardization, fields with yields between 10 and 110 ton/ha were selected. These thresholds were defined based on personal communication with specialists[1].

2.2.2.2. Varieties

Potato varieties were corrected for possible spelling mistakes and converted to lowercases to avoid noise in the data analysis. The varieties selected for further analysis must fulfil two criteria: having the largest number of observations in the dataset (number of crop fields with the same variety) and be present in the three years considered for this study. The varieties found in ≥ 40 fields of ware potato, ≥ 25 fields of starch potato and ≥ 20 fields in seed potato were considered for the analysis.

2.2.2.3. Location of crop fields

Maps were created to define the different regions for further analysis. Figure 1 shows the distribution of the fields using decimal coordinates in year 2017 (for years 2015 and 2016, see Figure A 1 in *Appendix A*). The map was created using QGIS (2.18.2).

[1] Specialist: Leon Spatjens and Abram Het Lam. AgroVision B.V

To assess the relation between the use of pesticides and field location, the area under study was divided in seven different regions. These regions were defined based on Diogo et al., (2017), comprising: West Holland, South West, South, East, Polders, North Coast and North East (Figure 2). Since GPS coordinates were not available for all crop fields, postal codes were used to locate the fields within the different regions. This allowed the inclusion of a higher number of fields in the analysis (see section 3.4.3 and Table A 1 in *Appendix A*).

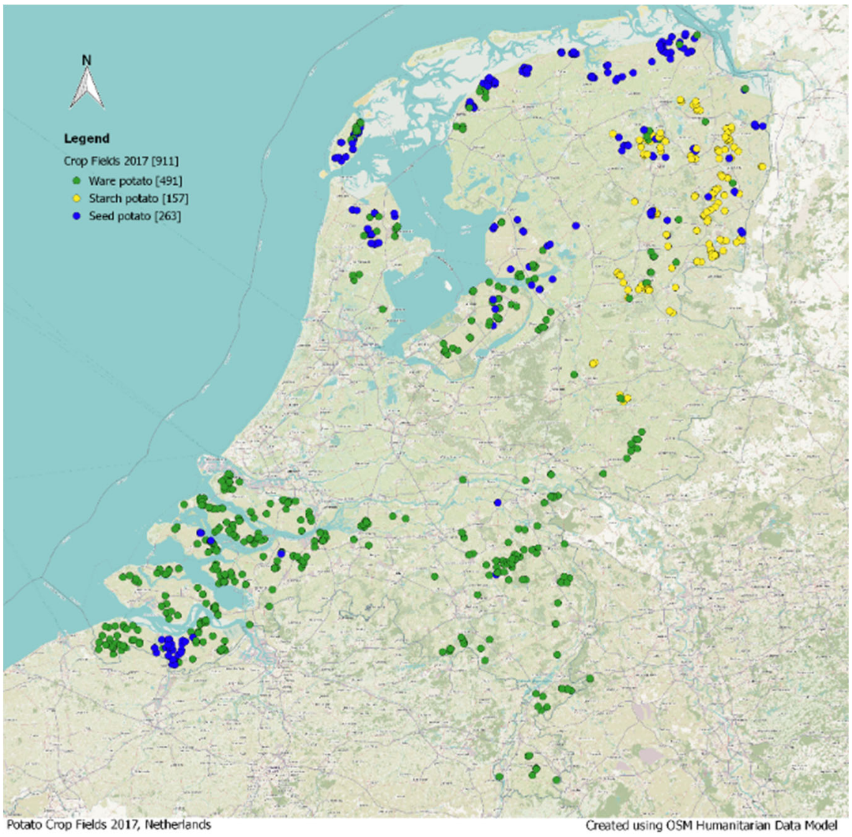

Figure 1. Location of crop fields in 2017 by crop type. Ware (green), starch (yellow) and seed (blue). Only fields with decimal coordinates available were used for visualization (n=911).

Region	*Diogo et al. 2017*	Labels
1	Bouwhoek en Hogeland	North Coast
2	Veenkolonien en Oldambt	North East
4	Oostelijk Veehouderijgebied	East
6	IJselmeer polders	Polders
7 8	Westelijk Holland Waterland en Droogmakerij	North West
11 12	Zuidwestelijk akkerbouwgebied Zuidwest Brabant	South West
13 14	Zuidelijk veehouderijgebied Zuid Limburg	South

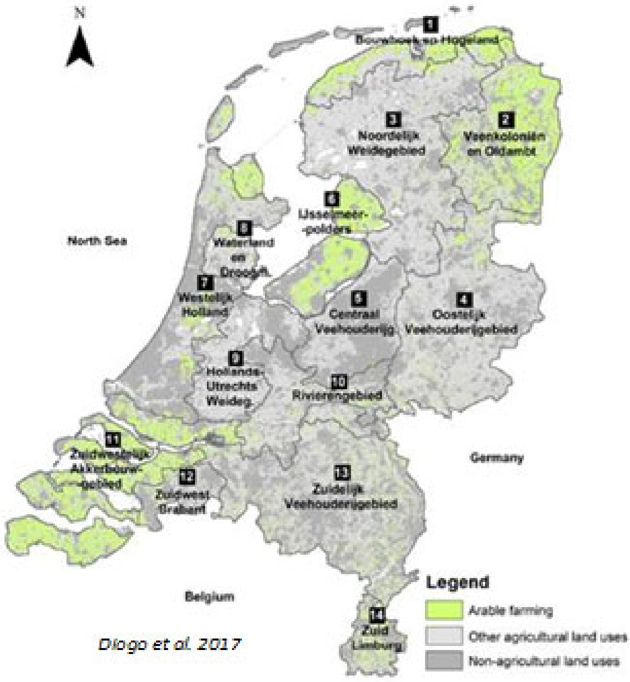

Figure 2. Agricultural regions in the Netherlands considered Regions in this research. Source: Diogo et al., (2017).

2.3. CALCULATED VARIABLES

2.3.1. Environmental impact points

The environmental yardstick for pesticides (EYP) developed by Center for Agriculture and Environment (CLM; (Reus & Pak, 1993) is a tool to score the impact of pesticide application on crop fields. This tool informs the users about the environmental impact of their crop protection strategies. The EYP calculates the impact of five criteria related to pesticide use: 1) risk for aquatic organisms (surface water pollution); 2) risk for soil organisms; 3) risk for infiltration to ground water; 4) risk for beneficial organisms and; 5) risk for health of the applier. These effects are scored as environmental impact points (EIP). This study considers criteria 1, 2 and 3 only. Information about criteria 4 and 5 was not available for all pesticide active ingredients.

The calculation of EIP on water organisms is based on the toxicity level of each pesticide towards the aquatic life. This calculation also accounts for the spray drift of the application (considered standard at 1%). The impact on ground water varies among seasons: slower rates of AI degradation due to low temperatures and rainfall surplus in autumn and winter (Sept 1st - Feb 29th) and increase risks of leaching for the applications done in spring and summer (March 1st – August 31st). The EIP calculation is based on a dose of 1kg/ha that must be multiplied by the total amount of pesticide applied per ha.

The calculation of EIP on soil organisms accounts for pesticides characteristics related to degradation rate, mobility, and soil organic matter (SOM) as it influences the concentration of AI that remains in the soil over time. For the calculation, 4 classes are defined based on %SOM (<1.5%, 1.5-3%, 3% - 6%, 6-12%, >12%). These SOM classes are also considered for the calculation of EIP on ground water. SOM can bind pesticide compounds, reducing their risk of leaching (CLM, 2018).

In the dataset used in this research, a reduced number of crop fields had information on %SOM. For this reason, crop fields with available GPS coordinates were used to increase the number of crop fields with information on SOM available for further analysis. Using ArcMap, the crop fields were located on the Dutch SOM map (Berg et al., 2017). The values on %SOM for each crop field were obtained from the map raster using the tool “extract values to points” (Figure 3).

Total **Environmental impact points (EIP/ha)** were calculated using the information provided by the environmental yardstick based on a dose of 1kg/ha of product applied. For instance, 1kg/ha of insecticide ACTARA considering 3-5%SOM has an impact of 810 EIP on soil organisms.

To calculate the total EIP/ha for each field, the following formula was used:

$$EIP_f = \sum_a (Pesticide\ EIP_a \times Dose_{af})$$

Where *a* is an index of each pesticides applied and *f* is an index that denotes each potato field. According to the equation, the total EIP of field f is the sum of the EIP of pesticide a times the dose applied of pesticide a in field *f* (kg/ha or l/ha).

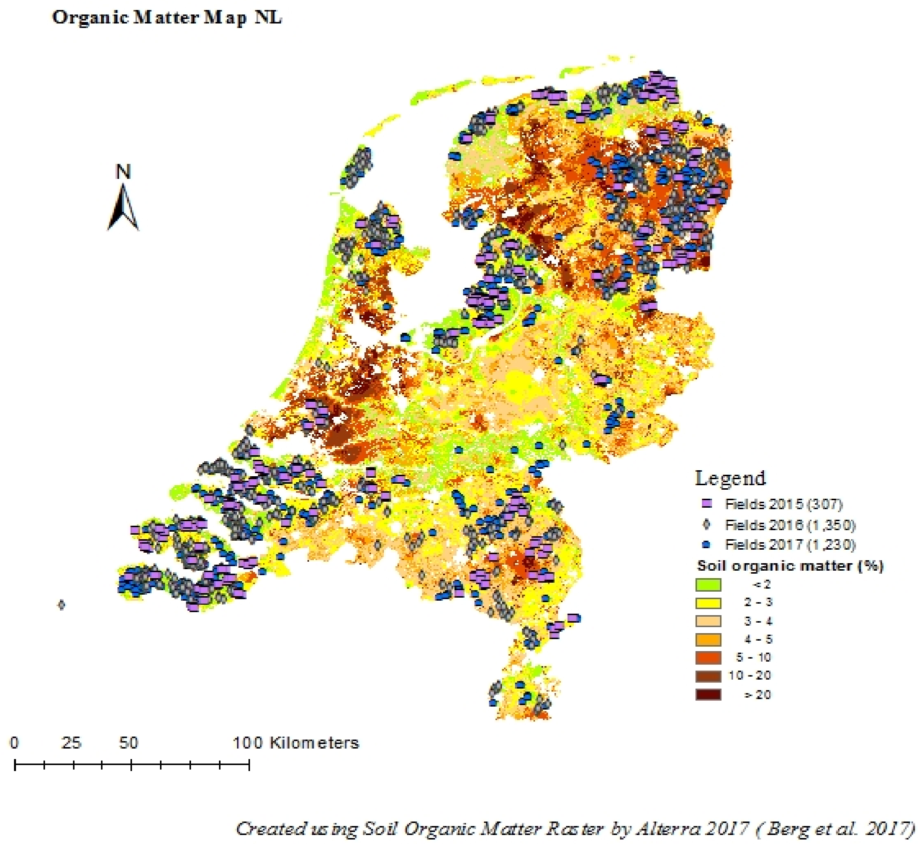

Figure 3. Crop fields located on SOM map (Berg et al., 2017) to extract information on %SOM (observations across all years are shown).

2.3.2. Active ingredient (AI kg/ha)

The calculations for number of sprayings were done in R using the "aggregate" function to sum up the number of spraying operations done per field during the growing cycle.

Total active ingredient (AI kg/ha) was calculated as:

$$Total\ AI_f = \frac{\sum_a (Dose_{af}\ \times\ AI_a\ \times Area_{af})}{Size_f}$$

Where the total AI kg/ha applied on field f is the sum of the dose of pesticide a (kg/ha or l/ha) times the AI of pesticide a (AI kg/kg or AI kg/l) multiplied by the area of field f applied with pesticide a (ha), divided by the total area of field f (ha).

2.4. STATISTICAL ANALYSIS

2.4.1. Data exploration

Boxplots were used to first explore the distribution of the data (ggplot package in R). The dependent variables considered were yield, number of sprayings, total AI and total EIP (Figure 5-7,10) and the independent variables were, year, crop type, region, and varieties. From this analysis we obtained the information on minimum and maximum values, quartile ranges, median and mean values for each variable across different subsets of the data. Observations below 1.5 the interquartile range (*IQR*), below the first quartile and above the 3rd quartile were considered as outliers.

2.4.2. Linear mixed models

Linear mixed models (LMM) allow to account for the variation of the response variables from different distributions. This characteristic is useful when analysing hierarchical data. Mixed models can incorporate fixed effects, as in linear regression, and random effects. Random effects represent the level of variation in addition to the noise term in common linear models. These random effects allow to give structure to the error term by assuming a different baseline response value for each factor.

The general form of the model in matrix notation is:

$$y = X\beta + Z\gamma + \epsilon$$

Where y is the N x 1 column vector of the outcome variable, X is the N x p matrix of the predictor variables (p) and β is the p x 1 vector of the fixed effect regression coefficients; Z is the N x q matrix for the random effects; γ is the q x 1 vector of the random effects and ϵ is N x 1 residual vector. It is assumed $\gamma \sim (0, \sigma^2 G)$, with G is the variance-covariance matrix of the random effects, and the residual $\epsilon \sim N(0,\sigma^2\ \epsilon)$ are independent.

The assessment of the relations between yield, total AI, number of sprayings, total EIP and the different crop management factors and regions was done applying LMM's. The analysis was done using the R packages "lmerTest'', "lmer4" and "predicted means" (Bates et al., 2015; Kuznetsova et al., 2017; Luo et al., 2014; Welham et al., 2004).Significant differences were assessed at a 0.05 confidence level. In this study, only random intercepts were analysed (random slopes were not considered). AIC values were used to evaluate the model goodness-of-fit.

The structure of LMM's estimated is shown in Table 2. LMM 1 was meant to give an overview of the relation between yield, the different crop types of potato and the variation between years. In this way, crop types and years were considered as fixed effects, including an interaction term between these variables. The dummy variables farm, region and variety were considered as random effect to control for the variability in the intercept for each of these variables. The random effect of Farm ID was considered as nested in the variable region, since we assume that a farm will always belong to the same region across years.

The number of sprayings can be an indicator of the total AI applied. In this sense, the aim of LMM 2 was to evaluate the differences in number of sprayings per crop type (fixed effect). The variables farm nested in region, variety and year were considered as random effects.

LMM 3 to 5 were meant to evaluate the relation between the amount of AI, crop management and biophysical conditions. In LMM 3, the dependent variable of total AI (AI kg/ha) was assessed to test differences between crop types and year (fixed effects), considering the variables Farm ID (nested), region and variety as random effects. LMM 4 was meant to evaluate the differences in total AI among varieties (fixed effect) with year, farm (nested) and region as random effects. This model was applied separately to each crop type, since varieties differ between ware, starch and seed potato. LMM 5 was used to evaluate total AI in response to different regions (fixed effect). In this model the variables year, farm, variety, and crop type were considered as random effects.

LMM 6 aimed to assess the relation between the environmental impact points, crop type and year. The dependent variable EIP was evaluated per crop type and year including an interaction term (fixed effects), with region, farm (nested) and variety as random effects.

Table 2. Linear mixed models (R notation) estimated for potato production systems in the Netherlands. Codes: ¨|¨ indicates crossed random effects and ¨/¨ indicates a nested random effect

Model	Response variable	Fixed effects	Random effects
LMM1	Yield	Year + Crop Type + Year * Crop Type	(1 | Region / Farm ID) + (1 | Variety)
LMM2	Number of sprayings	Year + Crop Type	(1 | Region / Farm ID) + (1 | Variety)
LMM 3	Total AI	Year + Crop Type	(1 | Region/ Farm ID) + (1 | Variety)
LMM 4	Total AI	Variety	(1 | Year) + (1 | Farm ID) + (1 | Region)
LMM 5	Total AI	Region	(1 | Year) + (1 | Farm ID) + (1 | Variety) + (1 | Crop type)
LMM 6	Total EIP	Year + Crop Type + Year * Crop Type	(1 | Region / Farm ID) + (1 | Variety)

2.4.3. Stochastic frontier analysis

Methods like stochastic frontier analysis (SFA) can be used to estimate production frontiers that represent the maximum possible output for a particular set of inputs (Cornwell et Schmidt, 2008). In the agronomical context, this function can be set as a benchmark to measure the Technical Efficiency (TE) of individual production systems. According to Silva et al., (2017b), the TE can be approached as: a) *Output oriented*, to obtain the maximum output per unit of input, an increase in output from A to B (i.e. yield) for a given amount of input A (i.e. kg of pesticide applied), and b) *Input oriented*, to obtain a given output (C) by minimizing the amount of input (a).

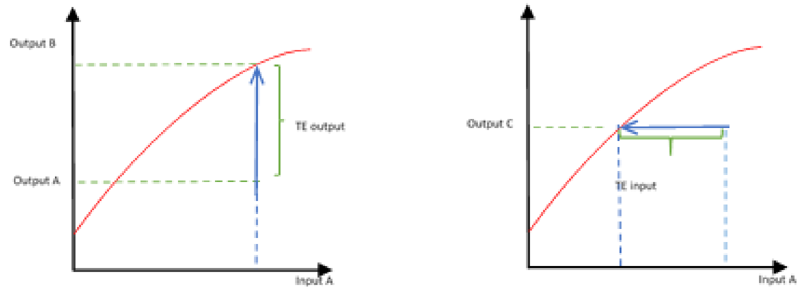

Figure 4. Production frontier and a) output-oriented technical efficiency and b) input-oriented technical efficiency. The x-axis represents the input level, the y-axis represents the output level and the red line represents the technical efficiency frontier for an input-output combination Based on Silva et al., (2017b).

The general form of a stochastic frontier is as follows:

$$y_i = f(x_i, \beta) + \ vi - ui \ (i = 1,2,3 \ldots N)$$

Where yi is the output of observation i, xi is the vector of inputs for observation i, β is a parameter vector and εi is the error term for observation i. The error term is composed by two independent components,vi and ui. The term $vi \sim N\ (0, \sigma 2)$ represents the usual two-sided statistical error and $ui \geq 0$ is a one- sided error term that represents technical inefficiency. The term *ui* thus measures the underperformance of a particular observation (Jondrow et al., 1982).

The stochastic frontier analysis was performed using the R packages “micEcon” and “frontier” (Henningsen, 2017; Henningsen & Coelli, 2017); The models were constructed adding independent variables gradually (Table 3) to assess the relation between yield and the amount of fungicides, herbicides and insecticides applied. The aim of Models 1 - 3 was to evaluate the effect of pesticide input per type. In models 4 – 6, dummy variables were added to capture the effect of year, variety, and soil type, respectively. In Model 7, the effect of potential quadratic effects of fungicide, herbicide, and insecticides were assessed, also to look for interactions among these pesticide types. Model 8 is the most complex model as it includes the terms of Model 7 plus interactions between pesticide types and soil types. The dependent variable yield and pesticide variables on pesticides were mean scaled and log transformed to perform these analyses.

Table 3. Stochastic frontier models (R notation) estimated for potato production systems in the Netherlands.

Model		Dependent variable	Independent variables
SFA1	sfa_fung	Yield	Fungicide
SFA2	sfa_herb	Yield	Fungicide + Herbicide
SFA3	sfa_inst	Yield	Fungicide + Herbicide + Insecticide
SFA4	sfa_year	Yield	Fungicide + Herbicide + Insecticide + Year
SFA5	sfa_vart	Yield	Fungicide + Herbicide + Insecticide + Year +Variety
SFA6	sfa_soil	Yield	Fungicide + Herbicide + Insecticide + Year +Variety + Soil type
SFA7	sfa_trlg	Yield	Fungicide + Herbicide + Insecticide + Year +Variety + Soil type + 0.5* Fungicide^2 + 0.5*Herbicide^2 + 0.5*Insecticide^2 + Fungicide*Herbicide + Fungicide*Insecticide + Herbicide *Insecticide
SFA8	sfa_trlg2	Yield	Fungicide + Herbicide + Insecticide + Year +Variety + Soil type + 0.5* Fungicide^2 + 0.5*Herbicide^2 + 0.5*Insecticide^2 + Fungicide*Herbicide + Fungicide*Insecticide + Herbicide *Insecticide+ Fungicide*Soil type + Herbicide * Soil type + Insecticide*Soil type

2.4.4. Yield level and boundary line

Fields were classified in three subsets according to their yield level. Three yield levels were defined: Ylow, Yav, and Yhigh for data analysis in section 3.8. Low yielding fields (Ylow) correspond to the first 20^{th} percentile, average yielding fields (Yav) are field with yielding between the 20^{th} and the 80^{th} percentile; and Yhigh corresponds to fields with yield above the 80^{th} percentile. After defining these terms mean values for yield, total AI/ha and EIP/ha were calculated for each yield level and crop type.

To represent the maximum yield response a boundary line was defined using yield as response variable and the total AI/ha and EIP/ha as independent variables. The points to fit the boundary line were selected using the following model :

$$y_{bl} = \frac{Ymax}{1 + (K\ exp\ )(-Rx))}$$

Where $Ymax$ is the attainable yield level for each crop, $K$and R are constants estimated with the nonlinear least square (*nls R function),* (Bates & Watts, 1988*;* Fermont et al., 2009*;* Silva, 2017a). The boundary line was fitted to a data subset with yield values below the 90^{th} percentile.

3. RESULTS

3.1. CROP FIELD DISTRIBUTION

According to the regions defined in section 2.2.2, crop types are present across the country in different proportions (Figure 5). Considering all years, ware potato fields were present in all regions: around 50% of ware potato fields were allocated in the South west region, followed by South and Polders (19% and 10%, respectively). Ware potato fields were also present in lower proportion in the North West and East (6% in each region), as well as North East and North Coast (3% and 3.5% respectively). The highest percentage of starch potato fields were located in the North East region (76%) followed by the East region (21%). Only a small proportion of starch potato fields was located in the South West and Polders regions (2% and 1%, respectively). Seed potato had a higher presence across the North, with 35% of the fields allocated in the North Coast and 23% in the North West region. Seed potato fields were also present at the South West (20%), followed by the North East (12%), the polders (7%), East (4%) and South (1%). Generally, the proportions of the potato crops found in each region is in line with the results found by Diogo et al. (2017). Further details about the distribution of each crop across the country are provided as supplementary material (Table B 1 and Figure B 1 in *Appendix B*).

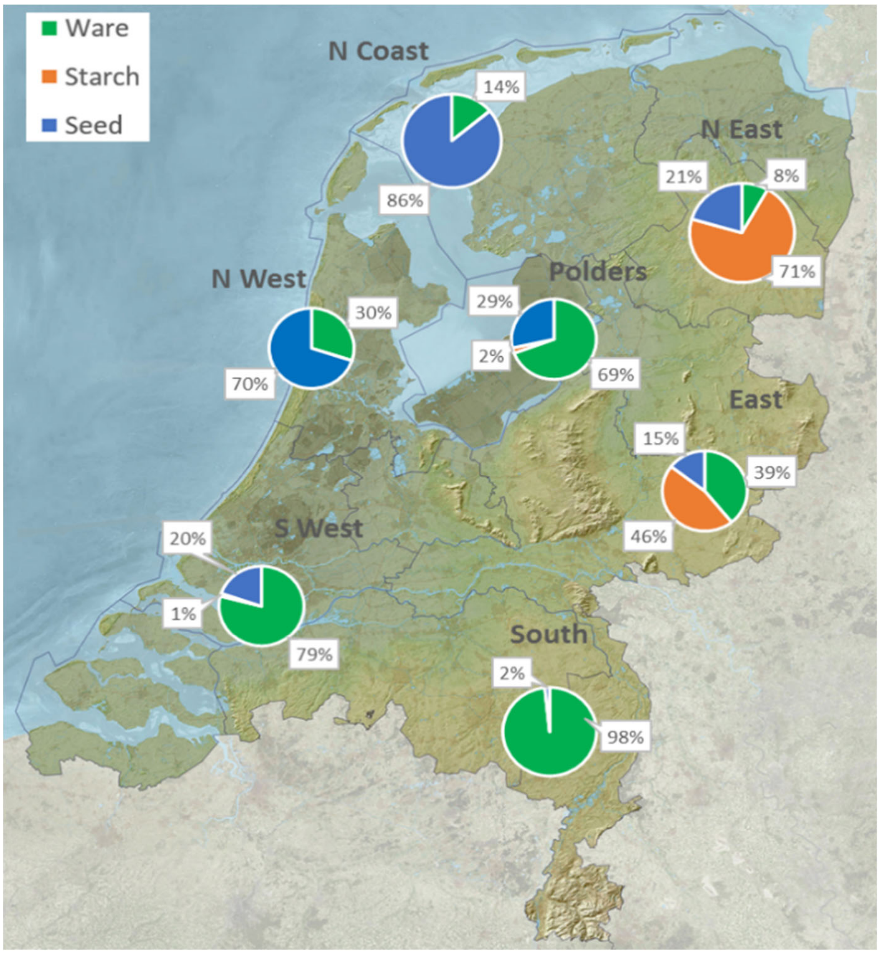

Figure 5. Percentage of crop fields of ware (green), starch (orange) and seed (blue) potato per region; years 2015-2017.

3.2. YIELD

A first exploration of raw data distribution showed subtle differences in yield among the three years. Median values for all crop types were lower in 2016 than in 2015 and 2017 (Figure 5). The differences in yield between crop types are more evident, ranging from 22.9 to 80 ton/ha for ware potato, 29.1 to 63 ton/ha for starch potato and 18.2 to 60.9 ton/ha for seed potato. Note that some outliers showed higher and lower yields. Further details about the distribution of potato yields per year and crop type are provided in supplementary material (Table C 1 in *Appendix C*).

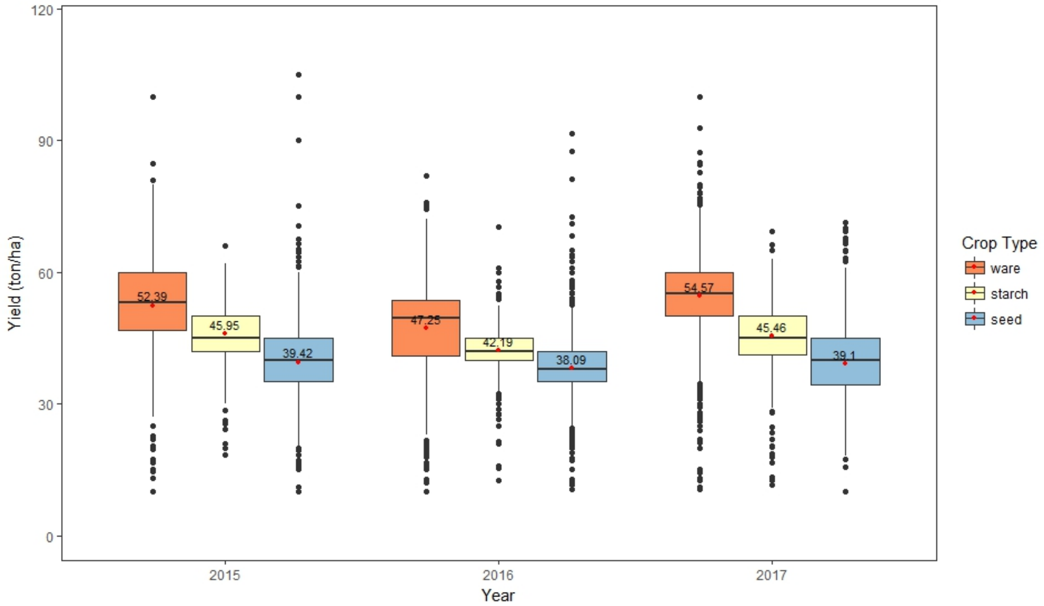

Figure 6. Yield (ton/ha) per crop type (ware, starch, and seed potato) per year (2015-2017). Red dots represent overall means.

The predicted means from the mixed model (LMM1; Table 2) showed that year and crop type had a significant effect on yield (χ^2=2067(8), p< 2.20E-16***, AIC 50047). The predicted means differed significantly in all years: 2016 had the lowest yield (43.2 ton/ha) compared to 2015 (46.1 ton/ha) and 2017 (47.1 ton/ha). Crop types also differed significantly, with 50.8 ton/ha for ware potato, 49.1 kg/ha for starch potato and 36.5 ton/ha for seed potato. The interaction between Crop type and Year was also found significant. Model outcomes are provided as supplementary material (Table D 1 in *Appendix D*).

3.3. NUMBER OF SPRAYINGS

The outcome of the linear mixed model (LMM2, Table 2) showed an effect of the crop type on the number of pesticide sprayings during the season (χ^2 =724, p< 2.2e-16 ***, AIC 33105). The number of sprayings was higher in starch potato fields (17), followed by ware potato fields (16) and seed potato fields (13) (see supplementary material, Table C 21 n *Appendix D*). The number of sprayings also differed across years: the predicted mean was 17 sprayings in 2016, 16 sprayings in 2015 and 15 sprayings in 2017. The data distribution (Figure 6) showed that 25% of ware potato fields were sprayed less than 14 times; 25 % of starch potato fields were sprayed 15 times; and 25% of seed potato fields were sprayed less than 11 times. The third quartile of ware and starch potato fields were sprayed between 17 and 19 times, while the third quartile of seed potato fields were sprayed around 15 times in the season. The maximum number of sprayings ranged between 21 - 26 times for ware and starch potato fields, and 19 to 21 times for seed potato (see supplementary material, Table C 2 in *Appendix C*).

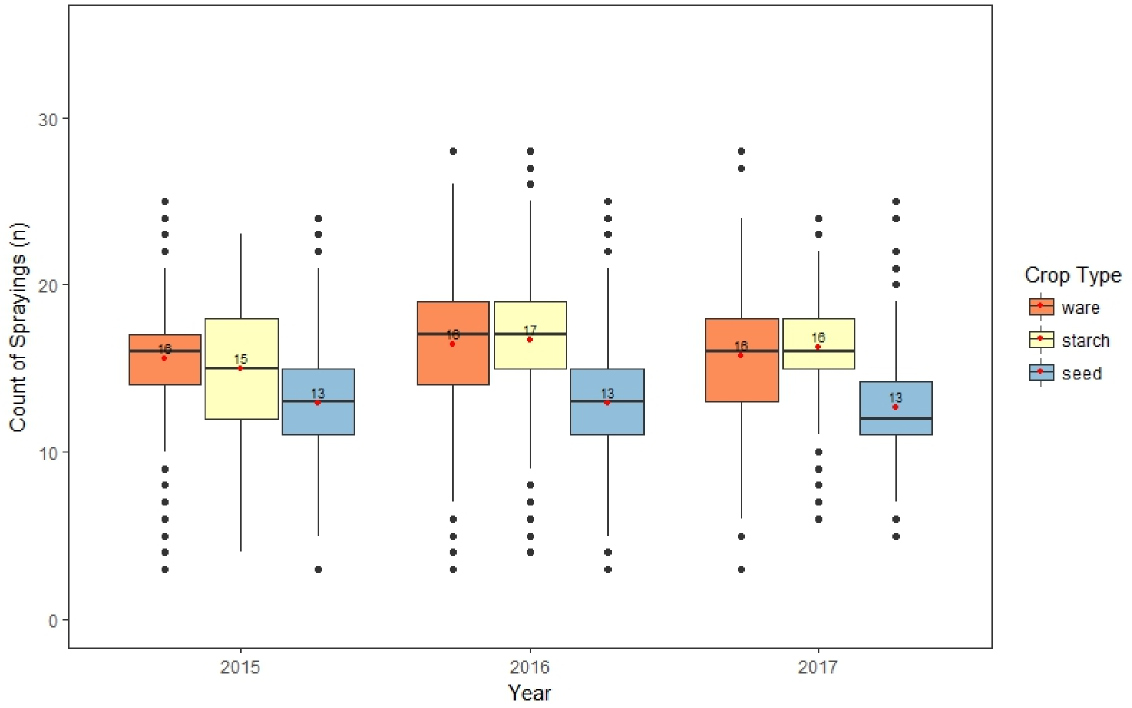

Figure 7. Number of sprayings per field in different crop types (ware, starch, and seed potato) per year (2015-2017). Red dots represent overall means.

3.4. TOTAL ACTIVE INGREDIENT (AI KG/HA)

3.4.1. Effects of crop types and year

Data distribution of Total AI showed the lowest median values for active ingredient (AI kg/ha) in seed potato: 8.6, 8.3 and 9.2 AI kg/ ha for 2015, 2016 and 2017 respectively (Figure 8). Starch potato fields showed the highest values with 11.1, 13.5 and 12.9 AI kg/ha for the same years. The median for ware potato remained around 10.5 AI kg/ha in all years. Quartile values differed among crop types. The first quartile of the population was lower or equal to 7.7 AI kg/ha in ware potato, 9.1 AI kg/ha in starch potato and 5.7 AI kg/ha in seed potato. For the third quartile, 75% of ware potato fields applied less or equal to 25.1 AI kg/ha, 24.5 AI kg/ha on starch potato and less or equal to 21.3 AI kg/ha on seed potato fields. In general, total AI ranged from 0.1 to 26.5 AI kg/ha. Further details about the distribution of total AI per crop type and here is provided as supplementary material (Table C 3 in *Appendix C*).

According to the model LMM3 (Table 2), there was a significant effect of year and crop type on Total AI kg/ha (χ^2=316.06 (4), p< 2.2e-16 ***, AIC 37604). The interaction between these factors was not significant, hence not included in the model. For all crop types, the predicted means of Total AI in 2015 (10.7 kg/ha) were significantly lower than in 2016 and 2017 (11.7 and 11.6 kg/ha). No significant difference was found between these two years. All crop types differed significantly, with the lowest predicted mean in seed potato

(10.9 kg/ha), followed by ware (11.4 AI kg/ha) and starch potato (12.7 AI kg/ha). Model outcomes are provided as supplementary material (Table D 1 in *Appendix D*).

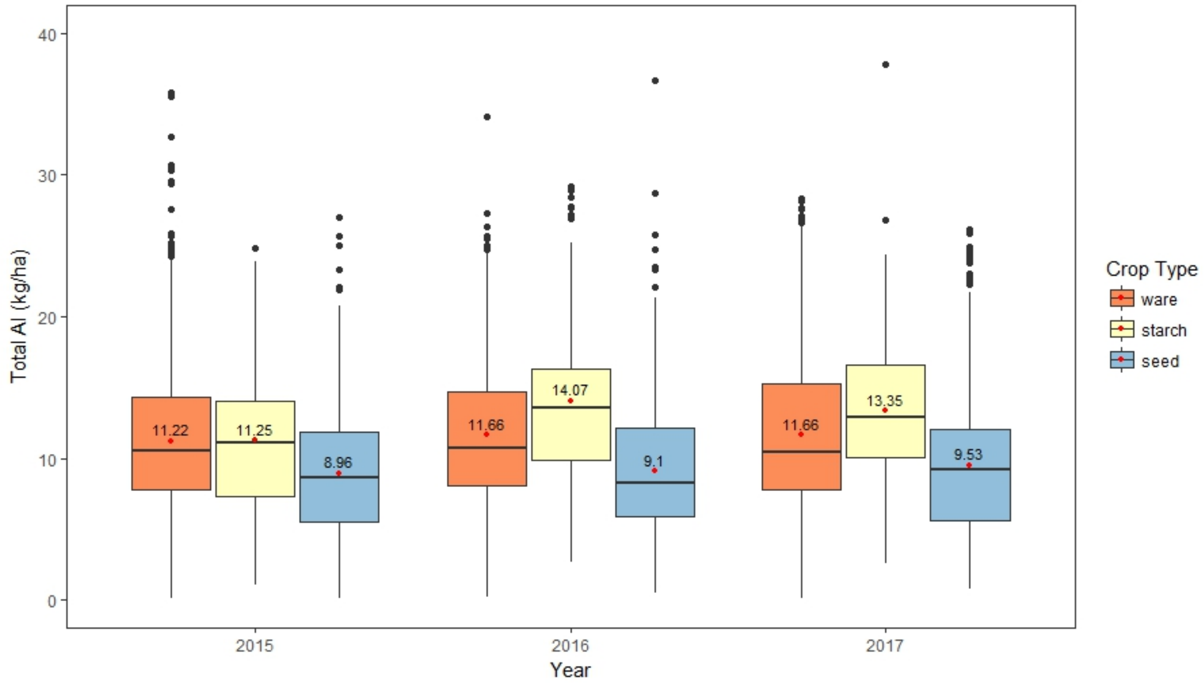

Figure 8. Total AI (AI kg/ha) per year (2015-2017) and crop type (ware, starch, and seed potato). Red dots represent overall means.

3.4.2. Effects of variety

The varieties showed an effect on the total AI applied (χ^2 =50.563, pval=1.063E-09***, AIC 7886) in model LMM4 (Table 2). The amount of AI applied (AI kg/ha) differed significantly between the selected varieties for each crop type (Figure 9). Among ware potato varieties, total AI applied in variety Melody (10.12 AI kg/ha) was significantly lower than the AI applied in Hansa (13.57 AI kg/ha), Fontane (12.61 AI kg/ha), Innovator (12.05 AI kg/ha) and Agria (11.90 AI kg/ha) (Figure 9a). In starch potato, the amount of total AI applied in variety Festien was significantly higher than Seresta (13.29 AI kg/ha and 12.14 AI kg/ha, respectively) whereas varieties Avarna, Altus, Novano, and Aveka did not differed significantly (Figure 9b). Seed potato varieties Spunta (8.88 AI kg/ha) and Innovator (8.69 AI kg/ha) were significantly lower than Fontane (9.86 AI kg /ha) and no significant differences were found for varieties Agatha and Agria (Figure 9c). Model outcomes are provided as supplementary material (Table D 2 in *Appendix D*).

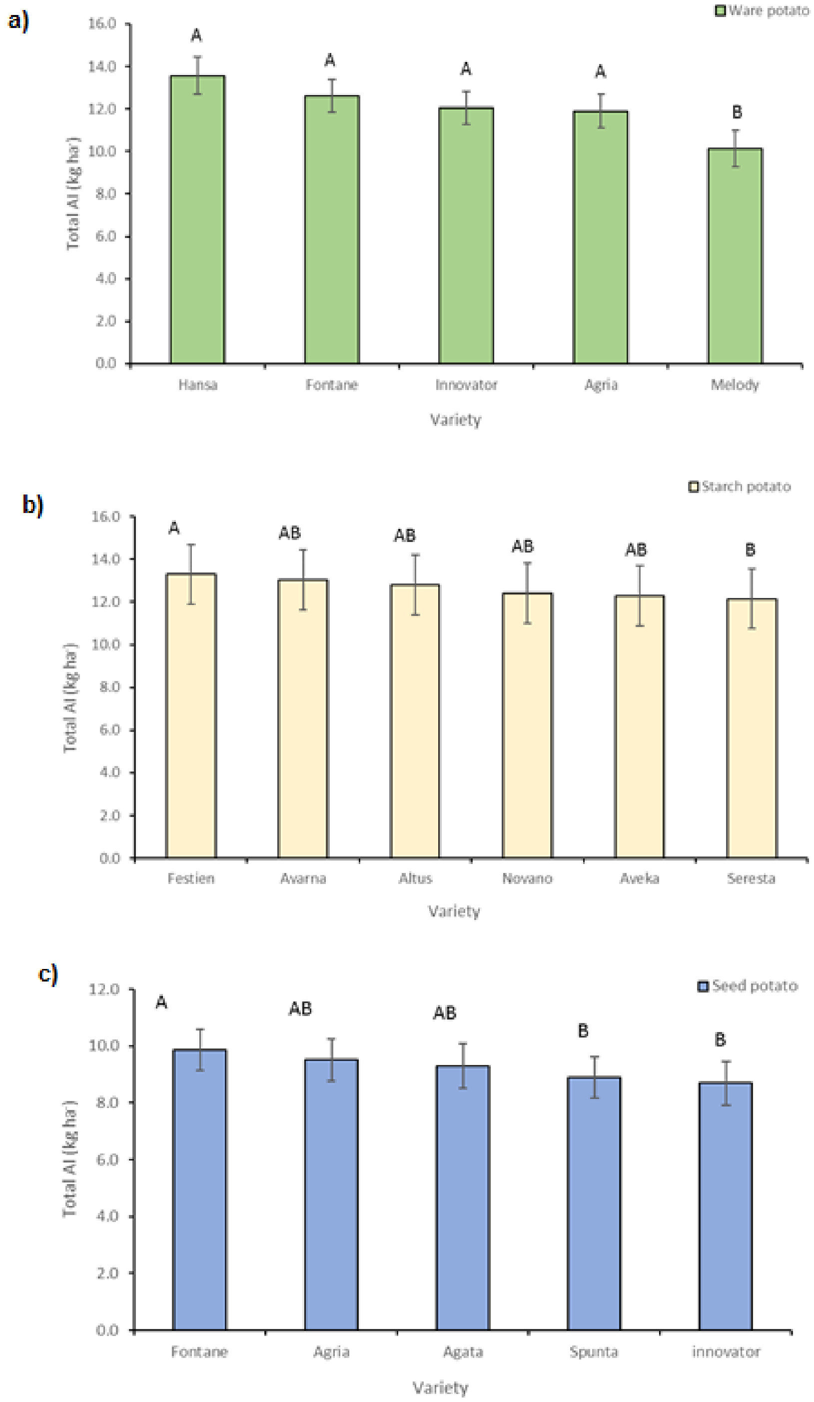

Figure 9. Predicted means of Total Active Ingredient (AI kg/ha) per variety of three different crop types: ware (a), starch (b) and seed potato (c).
Error bars represent the standard error of the mean. Different letters represent significant differences at 5% confidence level. (LMM3)

3.4.3. Effects of region

The model LMM5 (Table 2) was applied to the full data set including all varieties and to a subset of the data containing the most commonly used varieties for each crop type (cf. Figure 8). Using the data subset, the outcome of the model showed an effect of region on total AI (χ^2=48.968 (6), p = 7.57E-09***, AIC 15326; Figure 10). North coast showed a significantly lower amount of AI applied (8.7 AI kg/ha) compared to North East, Polders, South West and South (>10 AI kg/ha). In the North West region, total AI applied (10.6 AI kg/ha) was significantly lower than the South (14.1 AI kg/ha). North East had significantly higher predicted means of total AI (13.4 AI kg/ha) than the North coast and South West regions (8.9 and 11.2 AI kg/ha). South West region showed significantly lower predicted means (11.95 AI kg/ha) than the South (14.08 AI kg/ha). This latter region was significantly higher than North coast, North west and South West but did not differ significanlty from the Polders, East and North East regions. Similar results were found when applying the model on the full database. Model outcomes are provided as supplementary material (Table D 3 and Table D 4 in *Appendix D*).

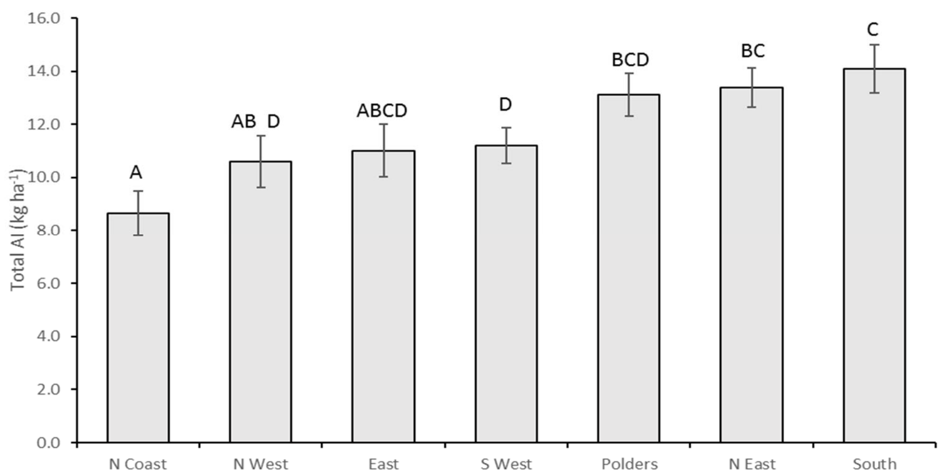

Figure 10. Total Active Ingredient (AI kg/ha) region and crop type for years 2017, 2016 and 2015. (Data subset for the most common varieties). Error bars represent the standard error of the mean. Different letters represent significant differences at 0.05 confidence level. (LMM5)

3.5. ENVIRONMENTAL IMPACT POINTS (EIP)

3.5.1. Effects of crop types and year

On average, the EIP's per ha ranged from 245 to 3636 EIP/ha in ware potato, 385 to 2094 EIP/ha in starch potato and 188 to 2638 EIP/ha in seed potato (Figure 11). Ware potato showed the highest median values (3201EIP/ha), followed by seed potato (2296 EIP/ha) and starch potato (2011 EIP/ha). Interquartile values ranged from 2384 to 4505 EIP/ha in ware potato, 1420 to 2536 EIP/ha in starch potato and 1400 to 3547 EIP/ha in seed potato. Details about the distribution of EIP per crop type and year are provided in supplementary material (Table C 4 in *Appendix C*).

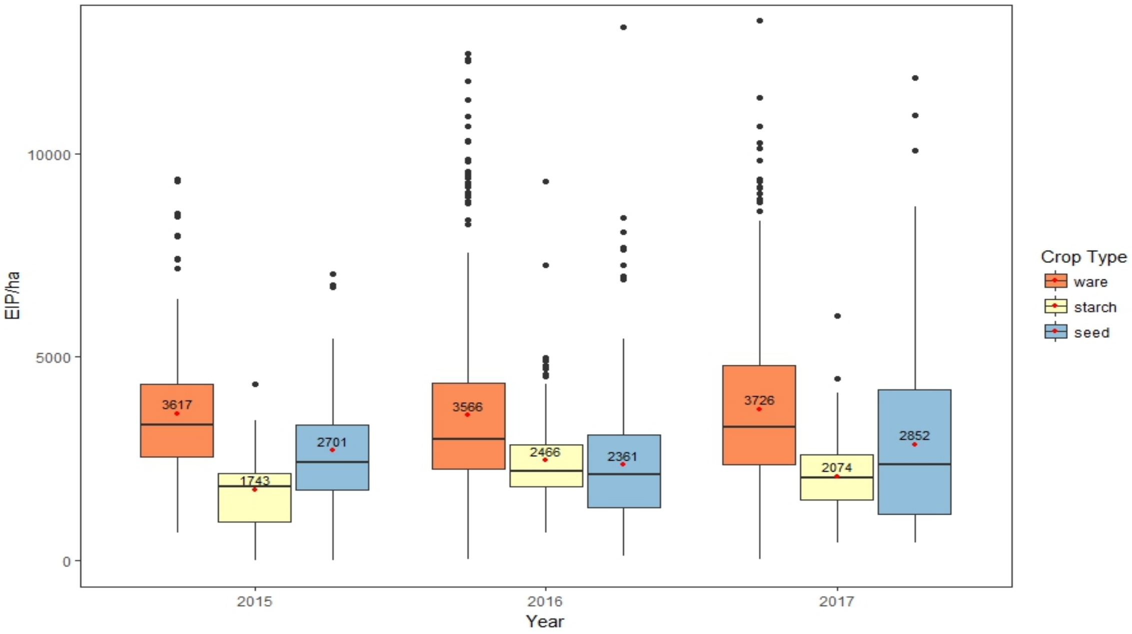

Figure 11. Total scores for environmental impact points (EIP) by crop type (ware, starch and seed potato) and year (2015 – 2017); red dots represent overall means.

Predicted means of EIP's/ha differed significantly in all years in model LMM6 (Table 2; $\chi2$=11.65 (13), p = 0.02***, AIC 39161). Year 2016 showed the highest value (3110.2 EIP/ha) followed by 2017 (2895.8 EIP/ha) and 2015 with the lowest value (2583.8 EIP/ha). According to LMMp, the EIP predicted means for seed potato (2561.4 EIP/ha) differed significantly from ware and starch potato (3029.7 and 2998.1 EIP/ha, respectively). Ware and starch potato did not differ significantly. The interaction between crop type and year was found significant. Model outcomes can be found in supplementary material (

Table D 5 in *Appendix D*).

3.5.2. Effects of pesticide treatments

The treatments applied on ware potato fields showed a higher impact on soil and aquatic life (Figure 12a). On average, 47% of the total EIP/ha were related to an impact on soil life; while 36% of the total EIP's were related to an impact on aquatic life and 17% to an impact on ground water. However, the maximum percentage of EIP related to the impact on soil life reached up 91%, 88% on aquatic life and 64% on ground water for certain fields. This means that crop fields differ in their impact on the environment depending on the pesticide treatments applied.

Starch potato fields showed a higher impact on soil life, followed by the impact on ground water and aquatic life (Figure 12b). On average 50% of the total EIP attained on starch potato fields, were related to the impact on soil life, 31% to the impact on ground water and 19% were related to the impact on aquatic life.

Seed potato fields showed a higher impact on soil life compared to the impact in aquatic life and groundwater. The impact on soil life represented and average of 66% of the total EIP, while 16% was related to aquatic life and groundwater 18%. The supplementary material shows the data distribution of the impact (%) on soil life aquatic life and groundwater separately (Table E 1 and Figure E 1 in *Appendix E*).

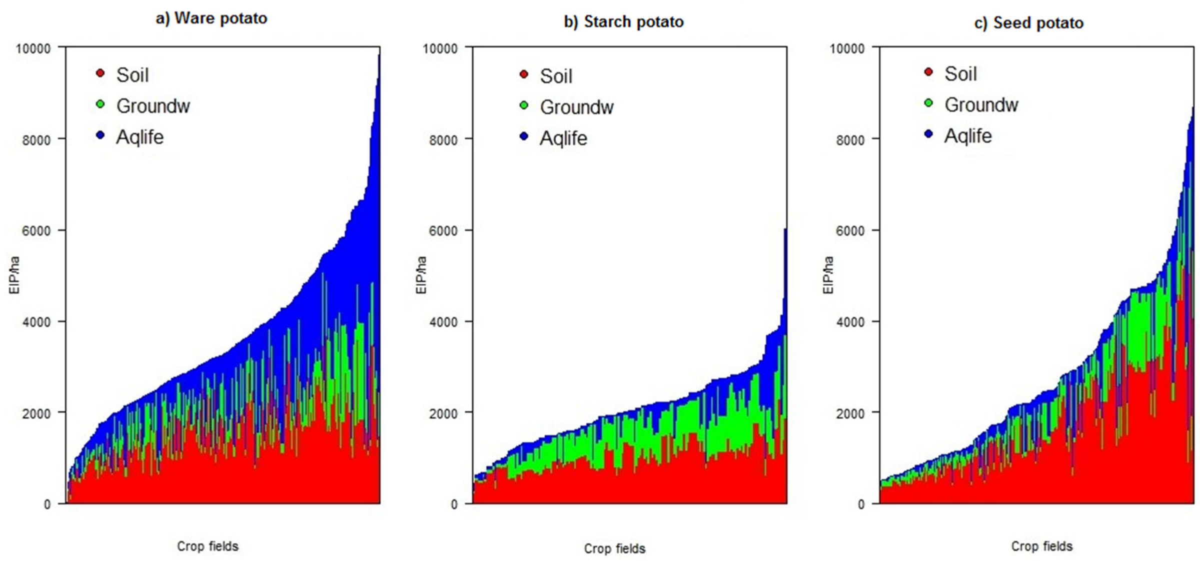

Figure 12. Proportion of the environmental impact points (EIP / ha) per environmental risk: Soil life (red), ground water (green) and aquatic life (blue) in a) ware, b) starch and c) seed potato. Each bar represents the EIP/ha of one field, year 2017. Results for other years can be found in Table 5.1A and Figure 5.1A (see supplementary material).

3.6. FUNGICIDES, INSECTICIDES AND HERBICIDES

3.6.1. Contribution to the total active ingredient per ha

Fungicides showed the biggest share of the total AI applied for all crop types (Figure 13a-c). In ware potato the average contribution of fungicide to total AI was 70%. Nevertheless, for three quarters of the fields, fungicides contributed up to 82% of the total AI. Herbicides mean contribution was 30% of the total AI. In contrast, the average contribution of insecticides to the total AI was negligible (0.7%) (Figure 13a).

Starch potato fields showed the highest average value of fungicide contribution to Total AI (85%), while herbicide contribution was 14% of the total AI applied (Figure 13b) and the insecticide average contribution was less than 1%. However, data distribution showed that for three quarters of potato fields, the share of fungicides, herbicides and insecticides reached up to 92%, 84% and 1% respectively, from the total AI applied.The average contribution of fungicides to total AI was 71% on seed potato fields (Figure 13c), followed by the contribution of herbicides (26%) and insecticides (3%). Further details about the contribution of each pesticide type to total AI is provided as supplementary material (Table E 2 and Figure E 2 in *Appendix E*).

In general, the three crops coincide with major contribution of fungicides to the total AI , most likely to prevent common fungal diseases like late blight. The slight difference in the amount of insecticides used in seed potato can be explained by pest and disease regulations on propagation material. These requirements may imply the control of insects that may act as a vector for spreading diseases.

3.6.2. Contribution to the environmental impact points

The contribution of fungicides, herbicides and insecticides to the EIP differed between crop types (Figure 13d-f). In ware potato fields, fungicides contributed on average with 63% of the total EIP while the mean contribution of herbicides and insecticides was 33% and 5% of the total EIP (Figure 13d), respectively. The contribution percentages per pesticide type are similar in starch potato (Figure 13e): fungicides contributed on average with the 71%, insecticides with 26% and herbicides with 4%.These mean proportions change in seed potato fields. In these fields, the average contribution of fungicides is lower than in ware and starch potato fields with 43% of the total EIP. The contribution of herbicides is similar to starch potato fields with an average contribution of 26%. However, the percentage of EIP generated by insecticides is much higher than in ware and starch potato fields (Figure 13f), with a contribution of 31% of the total environmental points observed in seed potato fields. Supplementary material (Table E 3 and Figure E 3 in *Appendix E*).

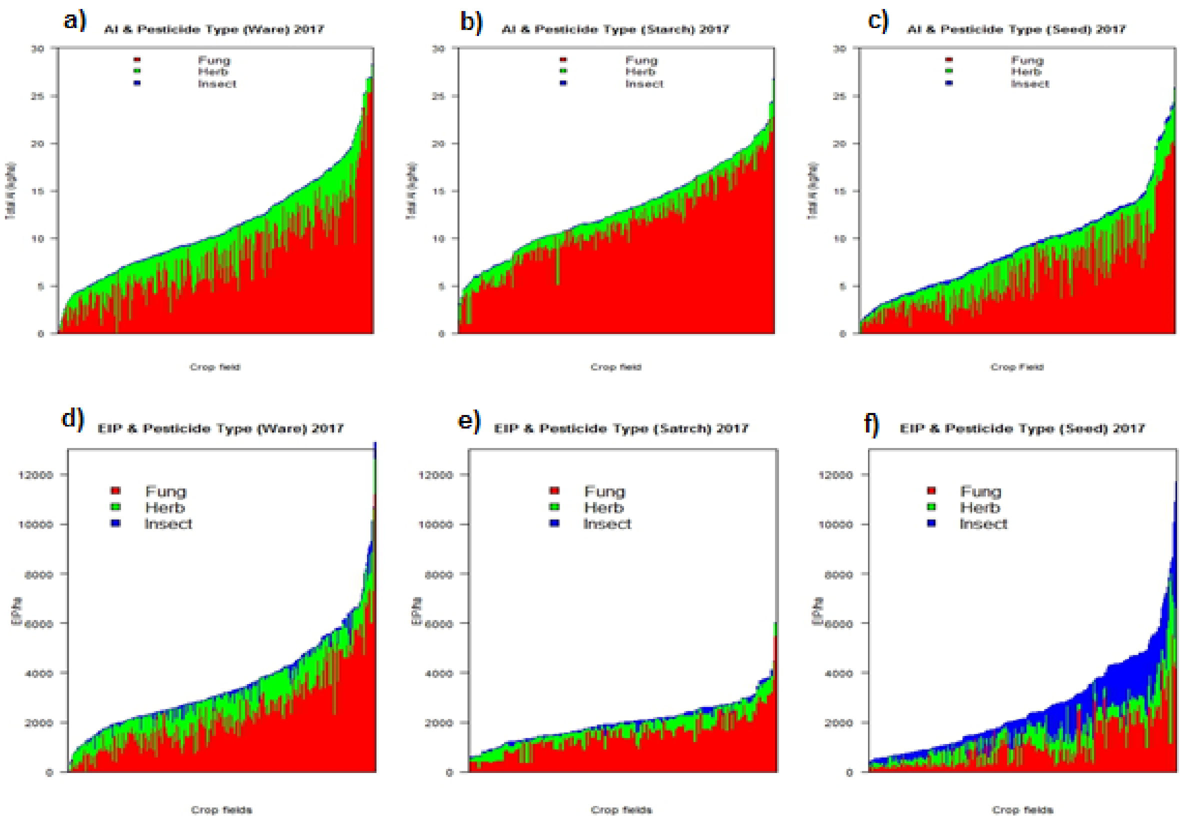

Figure 13. Contribution of fungicides (red), insecticides (blue) and herbicides (green) to the a-c) total active ingredient (AI kg/ha) and d-f) environmental impact points (EIP/ha) for each crop type (ware, starch and seed potato). Each bar represents the values of total AI/ha and EIP/ha of one field in year 2017.

3.7. STOCHASTIC FRONTIER ANALYSIS

Fungicides showed a significant positive effect (0.1% significance level) on yield of ware potato fields (models SFA1 - 5; Table 4). The significance changed in model SFA6 (1% significance level) when the variable soil type was added to the model. The effect of year on yield was found significant (at 0.01% significance level): the yield obtained in 2016 was significantly lower compared to those obtained in to year 2015. This effect was consistent in models SFA4 - 8. The variety Melody had a significant positive effect on yield at 5% significance level (models SFA5 and M6). The interaction between herbicide and insecticide, was found significant in model SFA8 as well as the interaction between insecticide and sandy soil, both were positive (significant at 5% significance level).

The effect of fungicide on yield of starch potato was only found significant at 5% significance level in model SFA8 (Table 5). There was a significant negative effect at 0.01% significance level on yield in 2016. Year 2017 also showed a negative effect significant at 5% significance level in models SFA4 - 7 and at 0.1% significance level in model SFA8. The yield of varieties Festien and Seresta was significantly lower compared to yield of variety Altus (model SFA8). Sandy soil had also a positive effect on yield in models SFA6 and SFA7 . The interaction between fungicide and insecticide was found positively significant at 5% level in model SFA7 and at 1% level in model SFA8; insecticides showed a negative effect on yield when in sandy soil, significant at 0.1% significance level (model SFA8). The results in model SFA8 need to be interpreted cautiously as the statistical test may be biased when $\gamma = 1$, due to a model misspecification that could bias the statistical test.

A positive significant effect of fungicides on seed potato yield was found in models SFA1 - 6 at 0.1% significance level (Table 6). In contrast to ware and starch potato no negative significant effect was found in year 2016 However, there was a negative significant effect in year 2017 in models SFA4 - 8. A negative effect on yield was found when fungicide and insecticide interact, significant at 5% significance level in models SFA7 and SFA8, as well as a negative effect at 1% significance level of the interaction between insecticide and sandy soil in model SFA8.

Based on the estimates of model SFA8, the mean technical inefficiency (or efficiency yield gaps) was smaller than 20% for the three crop types (Table 4, Table 5, Table 6). The mean technical efficient yield (YTeff) in ware potato was 64.21 t/ha while the mean actual yield (Ya) was 54.08 t/ha (Figure 14a). The mean value for the efficiency yield gap (EffYg) was 15.22%, meaning that ware potato yield can increase around 10 t/ha, if the efficiency in the use of inputs is improved. In starch potato, the mean values for YTeff and Ya in starch potato were 51.89 t/ha and 43.31 t/ha, respectively (Figure 14b), while the mean EffYg was 16.6% (~9 t/ha). The Ya obtained in seed potato was 40.0 t/ha with a mean EffYg of 15.21% (~7 t/ha), and YTeff was 47.9 t/ha (Figure 14c).

*Table 4. Stochastic Frontier models for pesticide use in ware potato production systems in the Netherlands. Reference values for dummy variables are: 2015 (year), agria (variety), clay (soil), east (region). Significance codes: '***' 0.1%, '**' 1%, '*' 5%.*

Crop1	**SFA1**	**SFA2**	**SFA3**	**SFA4**	**SFA5**	**SFA6**	**SFA7**	**SFA8**
Variables								
Intercept	0.319 ***	0.320 ***	0.321 ***	0.329 ***	0.316 ***	0.320 ***	0.338 ***	0.341 ***
Fungicide	0.065 ***	0.064 ***	0.070 ***	0.067 ***	0.072 ***	0.052 **	0.043 .	0.037
Herbicide		-0.011	-0.011	-0.010	-0.011	-0.009	-0.013	0.012
Insecticide			0.003	-0.004	-0.001	0.014	0.005	0.003
Year_2016				-0.108 ***	-0.104 ***	-0.113 ***	-0.118 ***	-0.120 ***
Year_2017				0.026	0.025	0.040 .	0.040	0.027
Variety_Innovator					0.009	-0.002	0.000	-0.004
Variety_Melody					0.077 *	0.077 *	0.060 .	0.058 .
Variety_Fontane					0.017	0.014	0.022	0.029
Variety_Hansa					-0.026	0.052	0.079	0.100 .
Soil_Loam						0.046	0.033	-0.176
Soil_Sand						-0.014	-0.010	0.034
Fungicide^2							-0.082 .	-0.075
Herbicide^2							-0.025	-0.051 .
Insecticide^2							-0.009	0.000
Fungicide x Herbicide							0.032	0.062 .
Fungicide x Insecticide							0.018	0.004
Herbicide x Insecticide							0.009	0.029 *
Herbicide x Soil_Loam								0.219
Herbicide x Soil_Sand								-0.073
Fungicide x Soil_Loam								-0.072
Fungicide x Soil_Sand								-0.076
Insecticide x Soil_Loam								-0.216
Insecticide x Soil_Sand								0.091 *
SigmaSq σ^2	0.081 ***	0.081 ***	0.071 ***	0.062 ***	0.061 ***	0.060 ***	0.060 ***	0.060 ***
Gamma γ	0.875 ***	0.877 ***	0.861 ***	0.855 ***	0.859 ***	0.849 ***	0.859 ***	0.877 ***
Sample (*n*)	470	470	395	395	395	326	326	326
Mean efficiency (%)	82.5	82.5	83.6	84.7	84.8	84.9	84.9	84.8

*Table 5. Stochastic Frontier models for pesticide use in starch potato production systems in the Netherlands. Reference values for dummy variables are: 2015 (year), altus (variety), peat (soil), east (region). Significance codes: '***' 0.1%, '**' 1%, '*' 5%.*

Crop2	**SFA1**	**SFA2**	**SFA3**	**SFA4**	**SFA5**	**SFA6**	**SFA7**	**SFA8**
Variables								
Intercept	0.068 ***	0.071 ***	0.060 ***	0.123 ***	0.142 ***	0.117 ***	0.143 ***	0.194 ***
Fungicide	0.010	0.013	-0.012	0.009	0.012	0.009	0.039	0.072 *
Herbicide		0.008	0.003	-0.001	-0.001	-0.003	0.025	-0.006
Insecticide			-0.004	-0.016	-0.017	-0.009	0.024	0.040
Year_2016				-0.107 ***	-0.108 ***	-0.104 ***	-0.102 ***	-0.117 ***
Year_2017				-0.061 *	-0.066 *	-0.064 *	-0.060 *	-0.070 ***
Variety_Festien					-0.019	-0.025	-0.032	-0.061 *
Variety_Seresta					-0.021	-0.024	-0.025	-0.046 *
Variety_Avarna					-0.009	0.003	-0.008	-0.061 .
Variety_Aveka					-0.024	-0.006	-0.012	-0.038
Soil_Sand						0.048 *	0.048 *	0.019
Herbicide^2							0.000	-0.015
Insecticide^2							0.028	-0.002
Fungicide^2							-0.040 .	-0.030
Fungicide x Herbicide							-0.048	-0.057
Herbicide x Insecticide							0.007	0.023 .
Fungicide x Insecticide							0.068 *	0.077 **
Fungicide x Soil_Sand								-0.026
Herbicide x Soil_Sand								0.052
Insecticide x Soil_Sand								-0.069 ***
SigmaSq σ^2	0.057 ***	0.057 ***	0.055 ***	0.056 ***	0.057 ***	0.056 ***	0.058 ***	0.066 ***
Gamma γ	0.919 ***	0.916 ***	0.926 ***	0.953 ***	0.959 ***	0.965 ***	0.981 ***	0.999 ***
Sample (*n*)	261	261	193	193	193	193	193	193
Mean efficiency (%)	84.4	84.4	84.7	84.5	84.3	84.3	84.2	83.4

Table 6. Stochastic Frontier models for pesticide use in seed potato production systems in the Netherlands.
*Reference values for dummy variables are: 2015 (year), agata (variety), clay (soil), N coast (region). Significance codes: '***' 0.1%, '**' 1%, '*' 5%.*

Crop 3	**SFA1**	**SFA2**	**SFA3**	**SFA4**	**SFA5**	**SFA6**	**SFA7**	**SFA8**
Variables								
Intercept	0.067 *	0.063 .	0.064 .	0.116 *	0.090	0.082	0.079	0.108
Fungicide	0.105 ***	0.107 ***	0.110 ***	0.103 ***	0.106 ***	0.099 ***	0.096	0.122 .
Herbicide		-0.011	-0.010	0.000	0.003	-0.001	-0.023	0.005
Insecticide			-0.007	-0.028	-0.041 .	-0.036	-0.074 *	-0.068 *
Year_2016				-0.024	-0.024	-0.024	-0.011	-0.004
Year_2017				-0.148 ***	-0.156 ***	-0.147 ***	-0.116 *	-0.137 **
Variety_Innovator					0.067	0.066	0.069	0.070
Variety_Spunta					0.070	0.056	0.029	0.019
Variety_Agria					-0.019	-0.015	-0.030	-0.036
Variety_Fontane					0.015	0.029	0.024	0.018
Soil_Sand						0.007	0.010	-0.041
Herbicide^2							-0.012	-0.007
Insecticide^2							0.027	0.002
Fungicide^2							-0.030	0.014
Fungicide x Herbicide							-0.015	-0.002
Herbicide x Insecticide							-0.001	-0.025
Fungicide x Insecticide							-0.076 *	-0.071 *
Fungicide x Soil_Sand								-0.015
Herbicide x Soil_Sand								0.045
Insecticide x Soil_Sand								-0.310 **
SigmaSq σ^2	0.078 ***	0.079 ***	0.078 ***	0.069 ***	0.069 ***	0.068 ***	0.062 ***	0.066 ***
Gamma γ	0.741 ***	0.737 ***	0.730 ***	0.701 ***	0.716 ***	0.713 ***	0.686 ***	0.766 ***
Sample (*n*)	218	216	212	212	212	197	197	197
Mean efficiency (%)	83.8	83.8	83.9	85.0	84.9	85.0	85.8	84.8

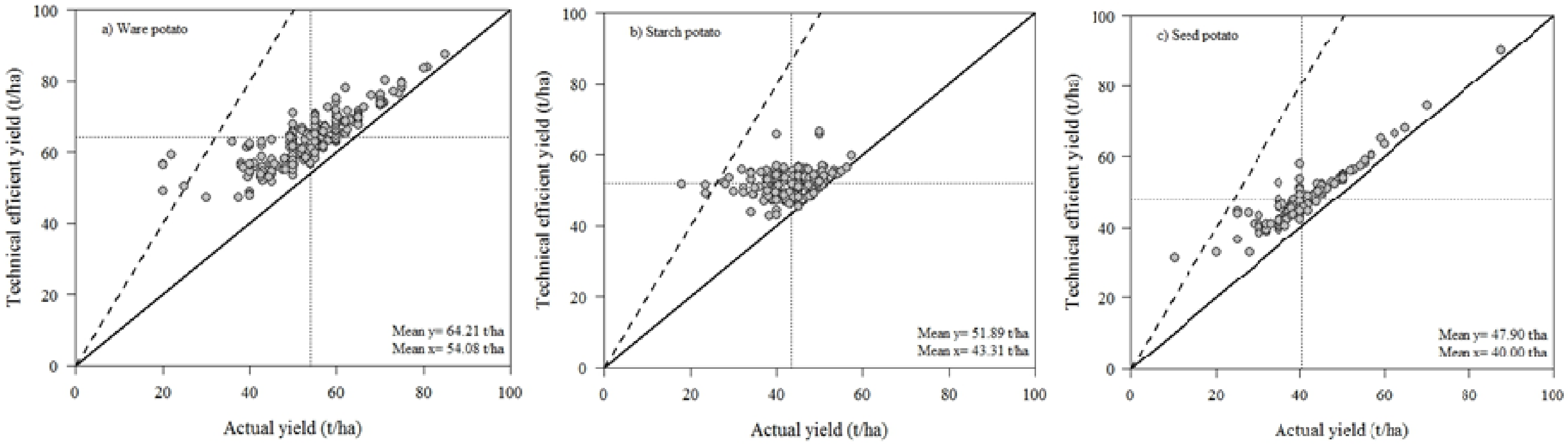

Figure 14. Relation between technical efficient yield and actual yield in a) ware, b) starch and c) seed potato, year 2015-2017. Lines represent the 1:1 relation (solid) and 1:2 relation (dashed) and mean values (dotted).

3.8. EIP, TOTAL AI, AND YIELD THE BENCHMARK

Ware potato yield reached the plateau around 70 ton/ha (output) and 6 AI kg/ha (input). Differences in mean AI input between Ylow and Yav (4 AIkg/ha) were larger than the difference between Yav and Yhigh (1 AI kg/ha) (Figure 15a). EIP thresholds (Figure 15b) showed that in ware potato, and for a given value of AI there is a wide range of EIP: This suggests that EIP/ha could be managed through the choices of pesticides included in pest and disease management. The mean value of EIP/ha in Yav (3811 EIP/ha) is 1227 EIP higher than Ylow (2584 EIP/ha). However, Yav showed narrow differences in EIP/ha (~15EIP) with Yhigh (3796EIP/ha). This suggest the Yav could improve yield level with a similar amount AI input and without an increase in the environmental impact (Figure 16a). Supplementary material (Table E 4)

In starch potato, yields reached a plateau at ca. 55 ton/ha and 5 AI kg/ha, (Figure 15c). The amount of AI kg/ha applied is quite similar among Yhigh, Yav, and Ylow (12.4, 12.1, and 12.2 AI/kg/ha respectively). This suggests that well performing fields (Yhigh) apply the same amount of AI with better results on yield than Ylow and Yav; Thus, the amount of AI kg/ha in Yhigh could represent a suitable threshold for AI input. Starch potato ranges of EIP/ha for a given input of AI had less variation than the one observed in ware potato (Figure 15d). This probably caused the similarity in the choices for pest management, possibly influenced by the proximity of starch potato fields (Figure 5). Narrow differences were observed in EIP/ha between Ylow (1906 EIP/ha) and Yav (1955 EIP/ha); Yav differed ~180 EIP/ha with Yhigh (2132 EIP/ha; Figure 16b). In this case the difference in yield between Ylow (28 ton/ha) and Yav (46 ton/ha) does not necessarily imply a substantial difference in EIP/ha.

For seed potato, yields reached plateau at ca. 50 ton/ha and 5 AI kg/ha , (Figure 15e). There is barely any difference in AI input between Ylow (10 AIkg/ha) and Yav (9.9 AI kg/ha), yet there was a 3.5 AIkg/ha difference between Yav and Yhigh. Concerning the EIP's, Yav and Yhigh differed 744 EIP/h; while Ylow and Yav, differed by 303 EIP/ha despite there was almost no difference in the mean input of AI /ha (Figure 16c, Figure 15). It is likely that this difference is influenced by the high environmental impact of insecticides used in seed potato production (Figure 13d). Supplementary material (Table E 4)

Minimum and maximum thresholds of EIP per kg of total AI kg were identified visually based on the distribution of the data (Figure 15b,d,f). The minimum threshold of EIP/AI kg was similar for ware starch and seed potato: 130, 100 and 140 EIP/AI kg, respectively. The maximum threshold of EIP/AI kg showed considerable differences between crops: the EIP per AI kg observed in ware potato was much greater (1300 EIP/AI kg) than the valued observed in starch and seed potato (550 and 400 EIP/AI kg, respectively). The mean values of EIP per unit of AI applied are 326, 167 and 203 for ware, starch, and seed potato respectively. (Supplementary material, Table E 4).

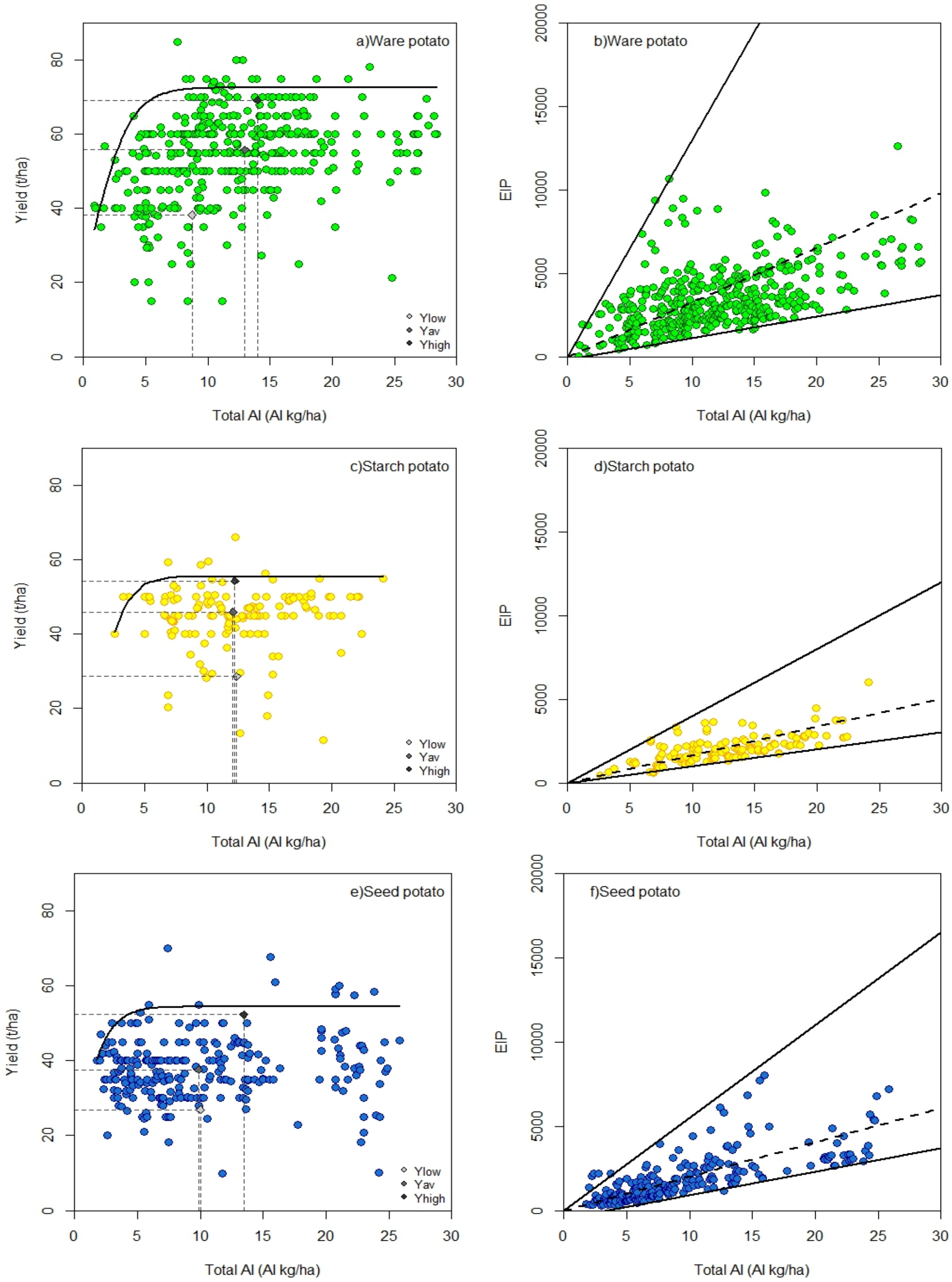

Figure 15. Yield, total AI and EIP in ware (a, b), starch (c,d) and seed (d,e) potato fields. On the left, boundary lines (solid) fitted using the observations above the 90th percentile for illustrative purpose and the mean input of AIkg/ha for Ylow, Yav and Yhigh (dashed lines). On the right, the EIP and total AI, lines are used for visualization of upper and lower values of EIP/AI kg (solid) and the mean ratio between EIP/totalAI (dashed). Data refers to year 2017.

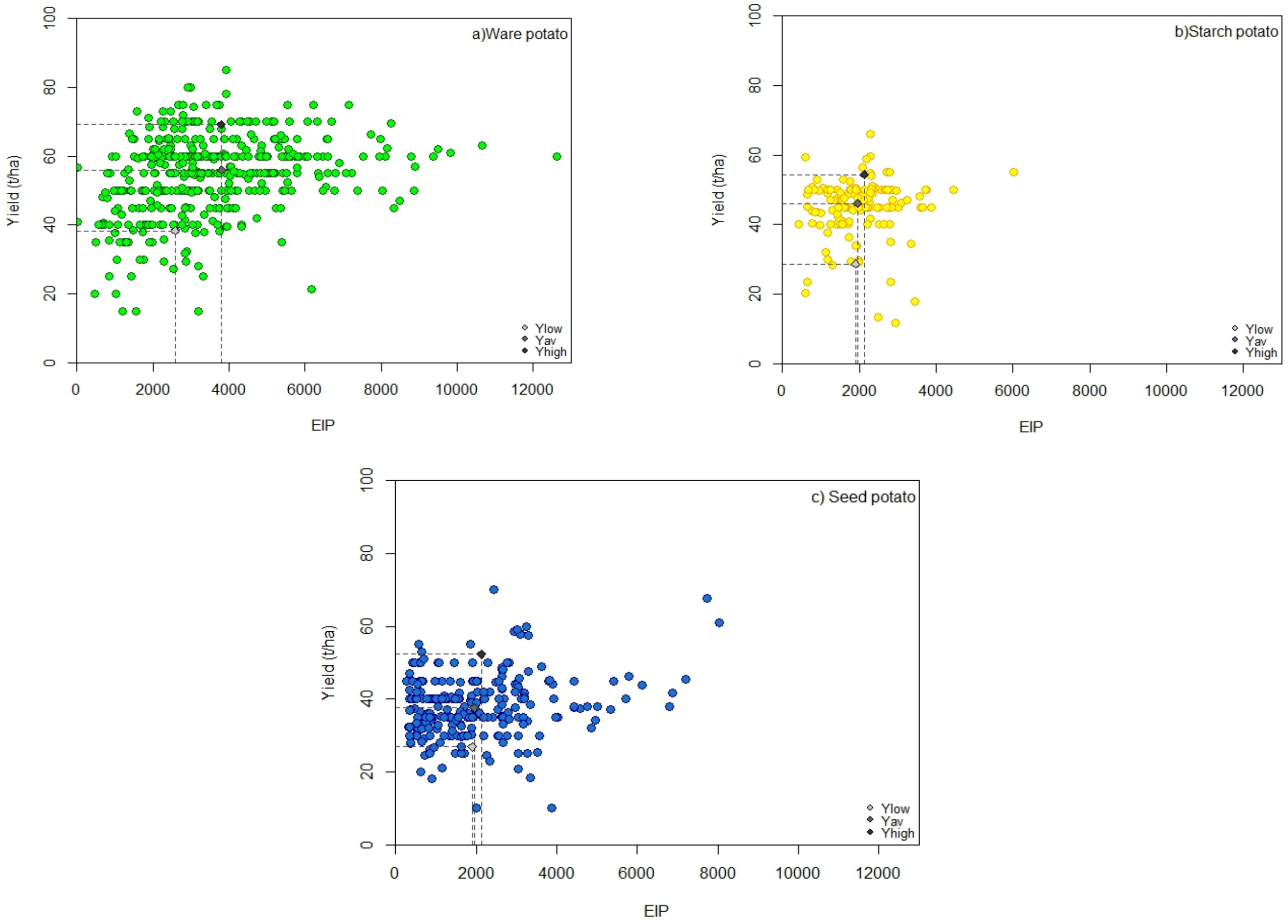

Figure 16. Yield and EIP of ware (a), starch (b) and seed (c) potato. Data refers to year 2017.

4. DISCUSSION

4.1. IS PESTICIDE USE INFLUENCED BY CROP MANAGEMENT?

Yield is influenced by the type of potato produced (Figure 5). Each potato type differs in the final purpose of consumption, and thus in their management practices. Even though all crops differed in total AI input per ha; main differences in pesticide use were found in seed potato when compared with ware and starch potato (Section 3.4.1). Crop management of seed potato is oriented to the production of small tuber size (25-60mm), free from fungal and virus diseases that could affect the progeny for potato production. (Allen et al., 1992). To fulfil these requirements, seed potato has usually a shorter growing period (Griffin, n.d.).

The growing period of seed potato is about 110 days, while mid late varieties of ware and starch potato can reach from 140 to 190 days , for this reason a lower number of spraying in this crop. Our results showed that ware and starch potato had 3 to 4 sprayings more than seed potato. In Haverkort & Hillier, (2011), similar results were found using Cool Farm Tool- Potato (CFT-Potato), with 9.5 sprayings vs 17 in starch potato. However, the author considered that spraying for crop protection in seed potato was more intense, as it was performed in a shorter period. Seen from this perspective, the number of sprayings is a limited indicator to assume that pesticide use in seed potato is more intense; nevertheless, total AI and EIP seem to give more insight on this issue and we will come back to it in the further sections.

Pesticide sprayings are often influenced by weather conditions during the growing season. High humidity is associated with fungal diseases. The risk of incidence of potato late blight outbreaks, can lead to an intensification in the use of fungicides for crop protection. This could explain a higher number of spraying in year in 2016 (Section 3.3). According to the climate indicator bulletins (CIB's), year 2016 showed high precipitation levels. A severe flood event was reported from 26th of June to 4th July with heavy rainfall affecting south-eastern France, Belgium and the southern part of the Netherlands and Germany (EURO4M, 2016). This could have influenced farmers decisions to avoid the risk of incidence of fungal diseases. The year effect on yield could also be related with weather conditions in 2016. Excessive humidity not only affects yield through foliage damage by fungal diseases, but also affects tuber quality and the timing of mechanical operations such as earthing up ridges for drainage (hilling) and weeding. This could have reduced the yield with 3 to 4 ton/ha in 2016 compared to year 2015 and 2017 (Section 3.2).

Even though the mixed model predicted a higher number of sprayings in 2016, total AI did not differ significantly from the amount of AI applied in 2017 (Section 3.3 & 3.4.1). Total AI can be influenced by type and number of pesticides in the mixture in the spraying tank. Therefore, it would be inaccurate to affirm that the number of sprayings could be directly related to total AI applied in one season. This could also explain why the difference between total AI applied in seed potato and the amount applied in ware potato is narrow (~1 AI kg/ha) despite having less spraying operations (Section 3.3 & Haverkort & Hillier, 2011) .

The use of resistant varieties is widely recommended in integrated pest management. Our result showed there are narrow differences in total AI/ha among the most common varieties in our study. Nevertheless, the amount of total AI kg/ha applied could be related with the characteristics of resistance towards early blight. According to the technical specifications of potato varieties described by the Netherlands Catalogue of Potato Varieties (NIVAP, 2011), ware potato variety Hansa, is classified as *susceptible (grade 4)* for late blight in foliage in a resistance scale from 3 (very susceptible) to 9 (very good). This variety accounted for the highest total AI kg/ha, opposite to the variety Melody which is *fairly susceptible* to *moderately resistant (5.5)*. Similar to seed potato varieties, Fontane with the highest total AI kg/ha is graded as *fairly susceptible to moderately resistant (5.5)* and Innovator with the lowest AI kg/ha graded with *good resistance (8)*. Starch potato varieties Festien and Seresta are similarly graded for late blight resistance, good *(8)* and fairly good resistance (*7)* respectively, but they differ in the time to reach maturity. Festien is classified as a very *late* variety (>120 days to reach maturity); while Seresta is classified as a *medium late* variety (110-120 days to reach maturity). The longer the crop remains on the field, the higher the risk of infection and the need of pesticide applications for its control.

Differences among may be influenced by the proportion of the crop types on each region. Studies performed in the past by Brower et al.(1994) identified Drenthe as the province with the highest amount AI applied, with 46 AI kg /ha. Major differences among regions were attributed to the use of nematicides and much smaller for the other products. In our study the province of Drenthe region could be comparable to the North East. Despite, nematicides were not included in this study, North East region is still among the highest values of AI (13 kg AI kg/ha); still, the amount of AI kg/ha applied had been reduced substantially in the current days. It is important to point out that the proportion of starch potato is higher in this region (Figure 5). Starch potato in this region has a rotation scheme of once every 2 years (2:1) with the cultivation of resistant varieties, while the recommended scheme is 4:1 (personal communication with experts[2]). Further research is needed insight the possible influences of the rotation scheme and pesticide use in this specific region.

4.2. HOW DOES PESTICIDE USE AFFECT THE ENVIRONMENTAL PERFORMANCE OF POTATO PRODUCTION SYSTEMS?

All crop types showed a major impact on soil life. Around 50% of the total EIP's in ware and starch potato and >60% in seed potato was related to this issue. However, crop types differed in their impacts on aquatic life and ground water. Ware potato had more impact in aquatic life, while starch potato had more impact on ground water and seed potato had similar impact in both environmental aspects (Section 3.5.2, Figure 13a-c). The fact that fungicides accounted for the highest share in both the total AI and total EIP/ha (Figure 13), suggests that this pesticide type is the major cause of the high environmental burden on soil life.

This assumption seems to be true for ware and starch potato (Figure 13d,e), but this is less clear for seed potato(Figure 13f). In this crop, a smaller share of insecticides in total AI/ha (26%) had a considerable impact 31% of the total EIP/ha; compared to the share of fungicides in total AI/ha (71%), that accounted for 43% of total EIP/ha. This is in line with the results obtained by de Snoo (2007), where insecticides represented 5% of the Dutch aggregate pesticide use (in kg), with 40% of the overall environmental burden. This is nearly the same burden of fungicides (42%), which are more intensively used.

It is worth to mention that seed potatoes have high quality standards requirements in terms of sanitary regulations. The prevention of viral diseases is a great concern in seed potato production and they are commonly transmitted by aphids and nematodes. This is probably the reason to increase the amount of insecticides used in crop protection. The high environmental impact of insecticides could explain then, the small difference in EIP/ha between seed potato and the other potato crops; despite having a shorter growing period, less sprayings and lower amount of total AI compared to ware and starch potato.

According to the specifications for EIP calculations (Section 2.1.3), high %SOM reduces the risk of pesticides leaching towards ground water. However, results in starch potato differed from our expectations; a major impact on ground water was found, regardless a high proportion of starch potato fields were located in areas of high %SOM (Figure 3, 4). Results in ware potato fields also differed from what was expected. Despite that ware potato fields were located in areas with low %SOM that favours leaching, the impact on ground water was lower than the impact on aquatic life. In this case, it is likely that the toxicity of the pesticide types (mainly fungicides) affects aquatic life more than their chance of being leached due to low %SOM.

The results of indicators for environmental assessment depend on the mechanisms behind its calculation and the purpose of the assessment as shown by Reus et al. (2002).The calculations of EIP depend on the pesticide's toxicity, %SOM and the season of application as explained in section 2.1.3. Therefore, the variation in the EIP is influenced by the great variety of combinations between the afore mentioned factors and the ample range of recommended dosages and farmers decisions. A deeper insight of the types of pesticides and dosage used for each specific crop could enlighten the origin of this environmental impacts for each crop type.

[2] Gerard Hoekzema, The Valthermond (WUR-PAGV), experimental fields.

4.3. ARE TOTAL AI, EIP AND POTATO YIELD RELATED?

Results from the Stochastic Frontier Analysis showed a significant relation between yield and pesticide use (AI kg/ha), though the effect on yield was mild (Section 3.7). This minor effect was somehow expected, but we were not sure to what extent yield could be affected. Our results showed a significant positive effect of fungicides on yield in ware potato fields; and a positive effect of herbicide and insecticide interaction. The interaction of fungicide and insecticide influenced yield positively in starch potato but negatively affected seed potato yield. According to Cedergreen (2014), synergistic interactions can be present in mixtures including insecticides (cholinesterase inhibitors) and "azole" fungicides that enhance the effect of these chemicals. It is likely that that these effects could indirectly affect yield.

Effects of some pesticide x soil interactions were also significant, ware potato yield was positively affected with the insecticide x sandy soil interaction, while seed and starch potato yield were negatively affected by this interaction. Results in Silva et al. (2017c), coincide on the positive effect of fungicides on ware potato, a positive effect when nematicides interact with fungicides in starch potato and the negative effects when pesticides interact with soil types in seed potato in this case fungicides and clay soil.

Results obtained by the stochastic frontier analysis confirmed a negative year effect in 2016 in ware and starch potato, also found with the linear mixed model (LMM1). Seed potato yield was more affected in 2017. Yield was only affected by certain varieties in ware and starch potato, still the effects were not consistent across models (Table 4, 5). Variety Melody positively affect yield in ware potato, while Festien and Seresta had a negative effect in starch potato (SFA 8). These varieties are classified with moderate or good resistance against late blight as discussed in section 4.1. In this case variety Melody could be a good choice to have a positive effect on yield and reduce AI input. In starch potato Festien a Seresta be a good option to reduce AI input, but yield could be slightly reduced. However, the choice of varieties depends on farmers priorities, that often entails more factors added to maximizing yield and reducing environmental impact.

High technical efficiencies close to 80% found in potato crops coincide with findings by Silva et al. (2017c). The mild effect of fungicide on yield, reflect that other factors in crop management have a stronger influence on yield (i.e. fertilization). However, it is likely that yield could be negatively affected if no pesticides are applied in conventional agriculture. Boundary lines used for analysis in section 3.8, (Figure 15a, c, d) show the AI levels at which the yield plateau is reached (~5 AI kg/ha). These values could be a starting point to identify possible thresholds in AI input.

It is important to point out that differences in AI input between high yielding fields (Yhigh), average yield (Yav) and low yield (Ylow) fields, is not always outstanding (Figure 15a, c, e). In ware potato Yhigh and Yav differed by 1 AI kg/ha; in starch potato all yield levels had a similar input of 12 AI kg/ha, and Ylow and Yhigh in seed potato had nearly the same AI input (~10 AI kg/ha). These results show that high yielding fields does not necessarily imply a high AI input, therefore low yielding fields with high AI inputs could reduce the amount of pesticide applied or increase their yield without increasing the AI input.

However, setting a threshold to reduce the environmental impact based on the amount of AI input could be somewhat arbitrary; as the amount of AI does not relate directly with the environmental impact and the environmental burden differ among pesticide treatments (Section 3.6.2, previously discussed in 4.2). Visually fitted lines Figure 15 b, d, f, show similar a lower threshold of EIP / AI kg applied among crop types (around 100-140 EIP). Unfortunately, upper thresholds are not that homogeneous. EIP per unit of AI in ware potato was higher than seed and starch potato; and there is a wide range of EIP attained to the same AI input level. Results suggest that pesticides combinations in ware potato are reaching higher levels of EIP, than starch and seed potato (Figure 13d, e, f). This reveals that the particular characteristics of every pesticide play an important role in environmental impact assessments and deserves to be further investigated.

If we look at the EIP values among yield levels (Figure 16b, c), the conclusions about environmental of increasing yields may diverge from the ones driven when looking to AI/ha (Figure 15a, c, e). In ware potato mean values of EIP/ha in Yhigh did not differed largely from Yav but differed widely from Ylow (+1227 EIP), suggesting that a shift from Ylow to Yhigh could imply an increase in environmental impact. In starch potato a similar mean input of AI in all yield levels (~12 AI kg /ha) , implied a ~180 to 220 EIP difference between Yhigh and lower yielding fields. Similar to seed potato where EIP values of Ylow and Yav had similar inputs of ~10 AI kg/ha but the difference in EIP is around 300 units. In the same crop, the difference in EIP between Yhigh and the two lower levels of yield of around 1050 EIP, that suggest that a shift of yield could represent a higher environmental impact. Nevertheless, high yielding fields present a wide range of EIP for a given yield level, which suggests that reduction in EIP values could be achieved.

5. CONCLUSIONS

Pesticide use in potato production and its relationship with yield and environmental impact is complex; it is mainly influenced by crop characteristics, production targets, climatic conditions, pesticide characteristics combined with farmers priorities and choices. Our study revealed that each potato crop differed in yield. Lowest yield was observed in seed potato (36.5 ton/ha) compared to ware potato (50.9 ton/ha) and starch potato (49.1 ton/ha). Crops also differed in the AI input per hectare, ware and starch potato applied respectively 1.5 kg AI/ha and 2.7 kg AI/ha more than seed potato (10kg AI/ha). The environmental impact measured as EIP was higher in ware and starch potato (c.a. 3000 EIP) compared to seed potato (2561EIP). Differences found in seed potato are attributable to a shorter growing season which aims to produce small tuber size convenient for seed tuber production.

We found a year effect on Yield, AI input and EIP. Year 2016 showed a yield reduction of c.a.8% compared to 2017 and 2015. AI input was higher in 2016 and 2017 (12kg AI), compared with 2015 (11 kg AI); while EIP differed among year with the highest value shown in 2016 (3110 EIP), followed by 2017 (-7% EIP) and 2015 (-20% EIP). Weather conditions of heavy rainfall reported on 2016 could be the main cause of this loss and the increase in crop protection measurements reflected as an increase of AI input and thus a higher EIP.

Varieties and also have an effect on AI input. Ware and starch potato varieties Hansa and Festien showed the highest AI input compared to Melody (10kgAI/ha) and Seresta (12. kgAI/ha); and Fontane showed a higher AI input (c.a.10kgAI/ha), than Innovator and Spunta (c.a. 9 AI kg/ha) in seed potato. Varieties of ware and seed potato with the highest AI input coincide with less susceptibility towards potato late blight in foliage. The variety of starch potato with the highest AI input have similar resistance characteristics as the variety with the lowest input but they differed in the length of the growing period. The AI input related to N Coast region was the lowest in the N Coast (8.7 AI kg/ha), while South accounted for the highest input (14.1AI kg/ha), the differences among regions could be probably bias by the difference the proportion of crop types with the highest AI inputs (ware and starch potato).

Results on pesticides environmental impact revealed that soil life is mostly affected by pesticide use in potato production. However, this effect cannot be directly attributed to the amount of AI input as EIP is calculated based on several factors. Insecticides in seed potato revealed that a small contribution to the total AI applied can have major consequences for the environment.

Pesticide input of fungicide showed a significant minor positive effect on yield, c.a. 0.07 ton/ha in ware and starch potato, and 0.10 ton/ha in seed potato. A negative influence on yield in 2016 was found to be significant in ware and starch potato (c.a.-0.10). The effect of the interaction fungicide x insecticides on yield was positive in starch potato but negative in seed potato; while the interaction between herbicide x insecticide positively affected yield in ware potato. The interaction between insecticide and sandy soil positively affected yield in ware and starch potato.

Yield plateaus showed a lower threshold in AI input (~ 5kg AI/ ha). Minimum thresholds of EIP per unit of AI are similar in ware, starch, and seed potato from 100-140 EIP; nevertheless, upper thresholds vary among crop types suggesting that pesticide combinations in ware potato (1300 EIP) have a higher environmental impact than seed (130 EIP) and starch potato (326 EIP). A wide range of EIP values were found for a given AI input suggests that pesticide pollution characteristics play an important role in the environmental impact of the fields.

Low yielding fields coincide with low EIP and AI, meaning that the environmental impact is lower that high yielding fields. This suggests that an increase in yield could imply also an increase in EIP values. Notwithstanding, the narrow difference in AI and EIP values between high average and high yielding, which suggests that a reduction on the environmental impact could be achieved without a major impact on yield. Values of AI and EIP of average and high yielding fields could be regarded as first targets value to comply the SDG 2 without a yield reduction.

Further research is needed to set accurate thresholds in for pesticide use. Pesticide combinations commonly used by farmers could be a good starting point to understand the environmental impact produced by each potato crop type. Farmers choices in pesticide use seem to be more related to risk perception than to potential environmental harm (de Snoo, 2007; Savary et al., 2012). The environmental performance of fields with decision support systems could also be used as reference in the search of suitable thresholds for pesticide reduction.

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APPENDICES

APPENDIX A *Location of Crop Fields*

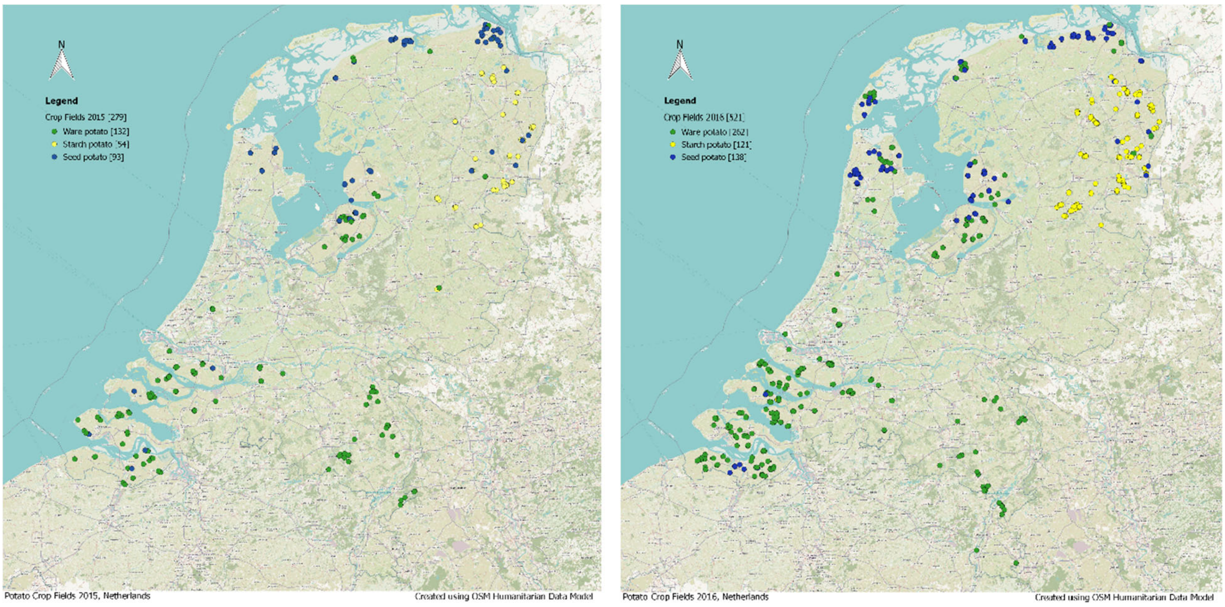

Figure A 1. Location of fields using decimal coordinates. Years 2015 (left) and 2016 (right).

Table A 1. Location intervals using postal codes

Region	4 digit Postal Code
N West	>=1000 <1200
	>=1400 <2200
S West	>=3100 <3400
	>=4300 <5000
South	>=5000 <6700
East	>=6900 <7800
	>=8100 <8200
Polders"	>=3800 <3900
	>=1300 <1400
	>=8200 <8300
N Coast	>=8700 <9200
	>=9900 <9999
N East	>=7800 <8000
	>=9300 <9800

APPENDIX B *Crop field frequency and percentage of fields per region*

Table B 1. Crop field frequency and percentages per region for three different crop types

Year	**2015**		**2016**		**2017**		
	Ware potato						
n	*1173*		*1482*		*1100*		Average %
Region	Freq	%	Freq	%	Freq	%	
N Coast	35	3.0	49	3.3	49	4.5	4
N East	41	3.5	57	3.8	19	1.7	3
East	77	6.6	89	6.0	61	5.5	6
N West	82	7.0	94	6.3	57	5.2	6
Polders	138	11.8	142	9.6	106	9.6	10
South	224	19.1	279	18.8	210	19.1	19
S West	576	49.1	772	52.1	598	54.4	52
	Starch potato						
n	*341*		*555*		*433*		Average %
Region	Freq	%	Freq	%	Freq	%	
N Coast	0	0.0	1	0.2	0	0.0	0
South	0	0.0	0	0.0	0	0.0	0
N West	1	0.3	0	0.0	0	0.0	0
Polders	2	0.6	3	0.5	6	1.4	1
S West	9	2.6	14	2.5	6	1.4	2
East	80	23.5	97	17.5	91	21.0	21
N East	249	73.0	440	79.3	330	76.2	76
	Seed potato						
n	*826*		*1057*		*595*		Average %
Region	Freq	%	Freq	%	Freq	%	
South	2	0.2	5	0.5	5	0.8	1
East	31	3.8	17	1.6	35	5.9	4
Polders	69	8.4	61	5.8	33	5.5	7
N East	96	11.6	122	11.5	71	11.9	12
S West	179	21.7	178	16.8	127	21.3	20
N West	210	25.4	289	27.3	96	16.1	23
N Coast	239	28.9	385	36.4	228	38.3	35

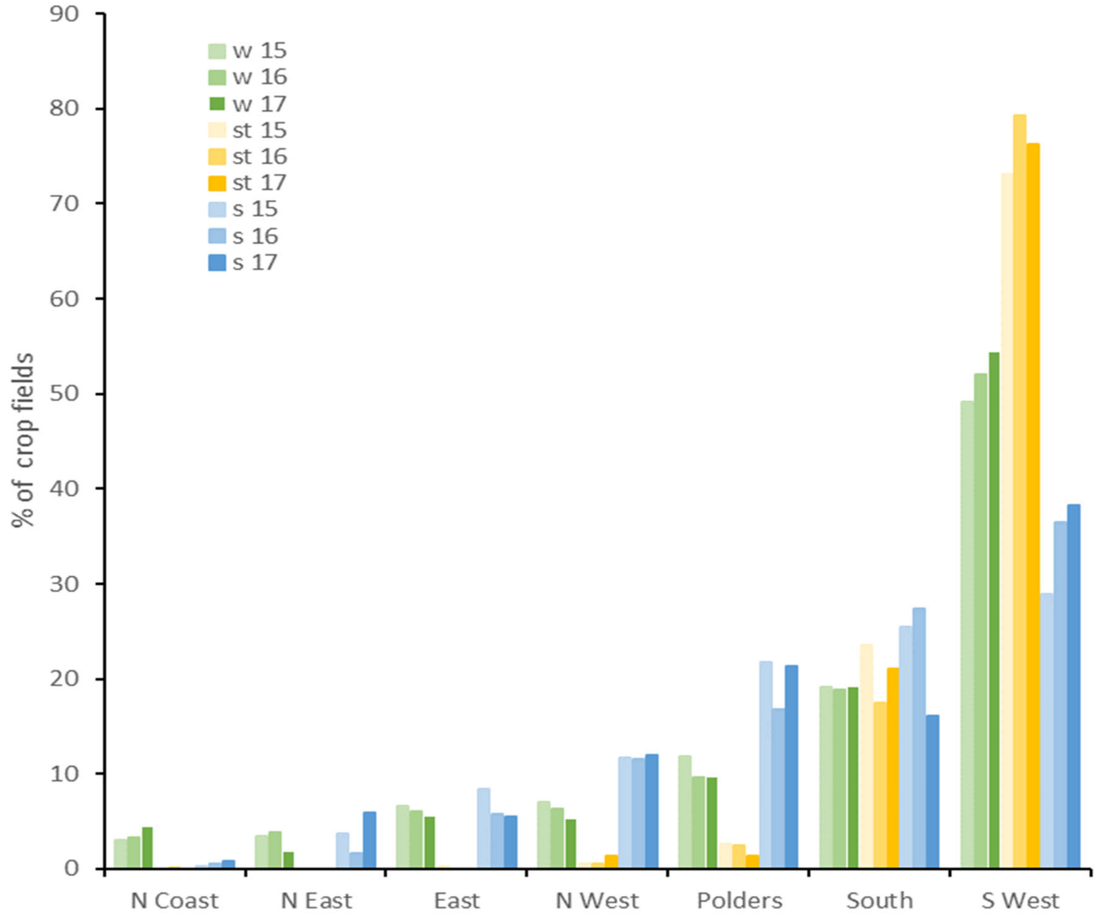

Figure B 1. Percentage of crop fields per crop type in seven regions of the Netherlands: ware (w, green), starch (st, yellow) and seed (s, blue). During three years of study 2015, 2016 and 2017 (15, 16, 17 respectively).

APPENDIX C *Data Distribution*

Table C 1. Data distribution of total yield (ton/ha) per year and per crop type

Year	2015			2016			2017		
	Ware	**Starch**	**Seed**	**Ware**	**Starch**	**Seed**	**Ware**	**Starch**	**Seed**
n	*1382*	*371*	*1029*	*1699*	*595*	*1258*	*1217*	*469*	*742*
Min	27.0	30.0	20.0	22.9	32.5	24.8	35.0	29.1	18.2
1st Q	46.6	42.0	35.0	41.0	40.0	35.0	50.0	41.3	34.2
Med	53.1	45.0	40.0	49.4	42.0	38.0	55.0	45.0	40.0
3rd Q	60.0	50.0	45.0	53.6	45.0	42.0	60.0	50.0	45.0
Max	80.0	61.9	60.0	72.0	52.3	52.5	75.0	63.0	60.9
Mean	52.39	45.95	39.42	47.25	42.19	38.09	54.57	45.46	39.1

** Outliers not shown (points outside 1.5 times the interquartile range above Q3 and below the Q1).*

Table C 2. Data distribution of number of sprayings per year and per crop type

Year	2015			2016			2017		
	Ware	**Starch**	**Seed**	**Ware**	**Starch**	**Seed**	**Ware**	**Starch**	**Seed**
n	*1384*	*370*	*1020*	*1695*	*596*	*1254*	*1208*	*469*	*736*
Min	10	4	5	7	9	5	6	11	7
1st Q	14	12	11	14	15	11	13	15	11
Med	16	15	13	17	17	13	16	16	12
3rd Q	17	18	15	19	19	15	18	18	15
Max	21	23	21	26	25	21	24	22	19
Mean	16	15	13	16	17	13	16	16	13

** Outliers not shown (points outside 1.5 times the interquartile range above Q3 and below the Q1).*

Table C 3. Data distribution of total active ingredient (AI kg/ha) per year and per crop type

Year	2015			2016			2017		
	Ware	**Starch**	**Seed**	**Ware**	**Starch**	**Seed**	**Ware**	**Starch**	**Seed**
n	*1382*	*371*	*1029*	*1699*	*595*	*1258*	*1217*	*469*	*742*
Min	0.1	1.1	0.2	0.2	2.6	0.5	0.1	2.6	0.8
1st Q	7.7	7.3	5.5	8.0	9.9	5.9	7.8	10.1	5.6
Med	10.5	11.1	8.6	10.7	13.5	8.3	10.4	12.9	9.2
3rd Q	14.3	14.0	11.9	14.7	16.3	12.1	15.3	16.6	12.1
Max	24.0	23.9	20.8	24.7	25.2	21.3	26.5	24.4	21.7
Mean	11.2	11.3	9.0	11.7	14.1	7.0	11.7	13.4	9.5

** Outliers not shown (points outside 1.5 times the interquartile range Q3 and below the Q1).*

Table C 4. Data distribution of environmental impact points (EIP/ha) per year and per crop type

Year	2015			2016			2017		
	Ware	**Starch**	**Seed**	**Ware**	**Starch**	**Seed**	**Ware**	**Starch**	**Seed**
n	*141*	*55*	*93*	*531*	*206*	*335*	*498*	*158*	*268*
Min	682	18	10	33	695	103	21	442	453
1st Q	2550	956	1742	2247	1813	1310	2355	1489	1146
Med	3324	1813	2419	2997	2186	2111	3284	2035	2358
3rd Q	4325	2134	3338	4377	2863	3102	4814	2612	4201
Max	6423	3443	5448	7551	4330	5445	8344	4130	8689
Mean	3617	1743	2701	3566	2466	2361	3726	2074	2852

**Outliers not shown (points outside 1.5 times the interquartile range above Q3 and below the Q1).*

APPENDIX D *Predicted means from the Linear mixed models (LMM)*

Table D 1. Predicted means of yield and total active ingredient (Total AI) per year and crop type. Letter-based representation of pairwise comparisons at significant level '0.05'.

	Model LMM1 Yield (t/ha)			Model LMM 2 Number of sprayings			Model LMM3 Total AI (AI kg/ha)		
Year	**Mean**	**SE**		**Mean**	**SE**		**Mean**	**SE**	
2015	46.1	1.18	A	14	0.50	A	10.8	0.65	A
2016	43.2	1.17	B	16	0.50	B	11.7	0.65	B
2017	47.1	1.18	C	15	0.50	C	11.7	0.65	B
Crop Type	**Mean**	**SE**		**Mean**	**SE**		**Mean**	**SE**	
Ware	50.9	1.17	A	16	0.54	A	11.5	0.65	A
Starch	49.1	1.24	B	17	0.60	B	12.7	0.67	B
Seed	36.5	1.18	C	13	0.56	C	10.0	0.65	C

Table D 2. Predicted means of total active ingredient (AI kg/ha) for the most frequent varieties within crop type (Model LMM4). Letter-based representation of pairwise comparisons at significant level '0.05'.

	Total AI (AI kg/ha)		
Ware potato	**Mean**	**SE**	
Hansa	13.6	0.9	A
Fontane	12.6	0.8	A
Innovator	12.1	0.8	A
Agria	11.9	0.8	A
Melody	10.1	0.9	B
Starch potato	Mean	SE	
Festien	13.3	1.4	A
Avarna	13.0	1.4	AB
Altus	12.8	1.4	AB
Novano	12.4	1.4	AB
Aveka	12.3	1.4	AB
Seresta	12.1	1.4	B
Seed potato	Mean	SE	
Fontane	9.9	0.7	A
Agria	9.5	0.7	AB
Agata	9.3	0.8	AB
Spunta	8.9	0.7	B
Innovator	8.7	0.8	B

Table D 3. Predicted means of Total AI (AI kg/ha) for different regions using a data subset of the most frequent varieties within crop type (Model 5). Letter-based representation of pairwise comparisons at significant level '0.05'.

	Total AI (AI kg/ha)		
Region	**Mean**	**SE**	
N Coast	8.7	0.8	A
N West	10.6	1.0	ABD
East	11.0	1.0	ABCD
S West	11.2	0.7	D
Polders	13.1	0.8	BCD
N East	13.4	0.7	BC
South	14.1	0.9	C

Table D 4. Predicted means of total AI (AI kg/ha) for different regions using all data base (Model 5). Letter-based representation of pairwise comparisons at significant level '0.05'.

	Total AI (AI kg/ha)		
Region	**Mean**	**SE**	
N Coast	9.1872	0.96447	A
N West	9.8531	0.99893	A
SWest	10.7016	0.88142	A
East	10.7463	1.04838	AB
N East	12.1712	0.92474	BC
South	13.4668	0.98833	C
Polders	13.4893	0.95831	C

Table D 5. Predicted means of environmental impact points (EIP/ha) for each year and crop type (Model 6). Letter-based representation of pairwise comparisons at significant level '0.05'.

	EIP/ha		
Year	**Mean**	**SE**	
2015	2583.8	342.6	A
2016	3110.2	335.1	B
2017	2895.1	336.0	C
Crop type	**Mean**	**SE**	
Ware	3029.7	334.8	A
Starch	2998.1	357.5	A
Seed	2561.4	340.8	B

APPENDIX E *Environmental Impact Points (EIP): Descriptive statistics and figures*

Table E 1. Percentage of EIP per environmental risk (soil life, ground water and aquatic life) per crop type and year.

Year	2015			2016			2017		
Ware (%)									
	Soil life	Gr water	Aq life	Soil life	Gr water	Aq life	Soil life	Gr water	Aq life
Min.	14.98	1.64	0.34	0.73	1.83	0.00	6.10	0.09	0.00
1st Q	38.18	7.49	12.81	35.93	7.87	21.08	35.53	8.14	18.06
Median	48.78	14.61	32.98	43.80	13.18	39.25	44.24	13.14	37.78
3rd Q	58.84	27.80	48.79	56.93	21.06	51.81	57.12	24.06	52.03
Max	87.60	57.86	83.38	90.27	80.00	87.59	94.68	53.23	93.81
Mean	48.23	18.75	33.02	45.82	16.01	38.17	46.74	16.74	36.51
Starch (%)									
	Soil life	Gr water	Aq life	Soil life	Gr water	Aq life	Soil life	Gr water	Aq life
Min.	26.78	5.51	0.00	20.43	3.27	0.00	18.29	3.40	0.00
1st Q	37.07	15.60	6.69	38.70	23.61	6.51	42.06	24.50	5.96
Median	44.06	29.23	14.63	46.90	31.21	16.58	50.71	30.32	10.54
3rd Q	63.34	45.57	25.20	55.81	38.73	31.04	61.94	38.32	27.75
Max.	80.51	66.67	67.71	86.73	61.95	71.81	89.20	58.86	71.62
Mean	50.07	32.19	17.74	48.36	30.93	20.71	52.85	30.22	16.93
Seed (%)									
	Soil life	Gr water	Aq life	Soil life	Gr water	Aq life	Soil life	Gr water	Aq life
Min.	19.25	5.90	0.00	3.77	0.93	0.00	10.99	2.83	0.00
1st Q	56.00	9.26	4.95	58.99	8.94	4.61	57.53	9.98	3.97
Median	69.03	11.87	11.68	68.68	15.02	11.94	66.78	15.25	10.28
3rd Q	79.31	22.83	23.02	79.17	25.13	18.19	75.82	27.24	19.02
Max	91.74	62.50	71.86	95.22	60.17	95.30	92.61	54.24	80.19
Mean	65.51	17.33	17.16	68.30	17.20	14.50	65.12	18.62	16.27

** Outliers not shown (points outside 1.5 times the interquartile range Q3 and below the Q1).*

Table E 2. Contribution (%) of fungicides, insecticides and herbicides to Total AI (AI kg/ha) per crop type and year.

Year	2015			2016			2017		
				Ware (%)					
	Fungicide	Herbicide	Insecticide	Fungicide	Herbicide	Insecticide	Fungicide	Herbicide	Insecticide
Min	12.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1Q	57.5	18.4	0.1	60.9	16.8	0.0	58.6	16.2	0.3
Med	70.0	29.4	0.5	73.6	26.0	0.4	71.9	27.5	0.6
3Q	81.1	41.6	0.9	82.6	38.5	0.8	83.0	40.6	0.9
Max	100.0	87.7	8.0	100.0	100.0	7.5	100.0	100.0	63.7
Mean	68.2	31.2	0.6	71.0	28.5	0.5	69.6	29.6	0.9
				Starch (%)					
	Fungicide	Herbicide	Insecticide	Fungicide	Herbicide	Insecticide	Fungicide	Herbicide	Insecticide
Min	0.0	0.0	0.0	28.2	0.0	0.0	18.3	0.0	0.0
1Q	78.3	8.0	0.0	82.5	6.6	0.0	83.7	7.9	0.1
Med	86.0	13.1	0.4	89.2	10.5	0.2	88.0	11.6	0.2
3Q	91.6	21.4	0.8	93.3	17.0	0.5	92.0	16.1	0.6
Max	100.0	100.0	2.8	100.0	70.3	4.8	100.0	81.2	66.4
Mean	83.1	16.4	0.5	86.7	13.0	0.3	85.8	13.6	0.5
				Seed					
	Fungicide	Herbicide	Insecticide	Fungicide	Herbicide	Insecticide	Fungicide	Herbicide	Insecticide
Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1Q	57.4	14.5	1.3	64.5	11.3	1.2	56.6	15.2	1.1
Med	70.2	25.3	2.6	77.4	20.0	2.2	72.7	24.3	1.8
3Q	82.8	38.8	4.5	85.9	32.8	3.7	83.0	40.8	3.3
Max	100.0	100.0	17.3	100.0	100.0	15.4	100.0	100.0	12.3
Mean	69.3	27.3	3.5	74.1	23.2	2.7	68.9	28.7	2.4

** Outliers not shown (points outside 1.5 times the interquartile range Q3 and below the Q1).*

Table E 3. Contribution (%) of fungicides, insecticides and herbicides to environmental impact points (EIP/ha) per crop type and year

Year	2015			2016			2017		
				Ware (%)					
	Fungicide	Herbicide	Insecticide	Fungicide	Herbicide	Insecticide	Fungicide	Herbicide	Insecticide
Min.	8.94	6.67	0.00	0.00	0.00	0.00	2.35	0.00	0.00
1st Q	49.46	22.33	0.02	55.61	19.47	0.01	54.91	19.81	0.03
Median	60.50	32.31	2.26	66.77	29.11	1.79	67.76	28.32	1.87
3rd Q	70.86	44.14	7.59	78.80	39.68	4.85	76.06	39.81	5.20
Max.	92.82	83.79	60.80	100.00	100.00	57.73	100.00	97.53	50.34
Mean	59.50	34.55	5.95	64.18	31.78	4.04	64.33	31.23	4.44
				Starch (%)					
	Fungicide	Herbicide	Insecticide	Fungicide	Herbicide	Insecticide	Fungicide	Herbicide	Insecticide
Min.	0.00	2.70	0.00	27.55	1.43	0.00	25.34	2.52	0.00
1st Q	37.05	12.70	0.02	66.31	10.33	0.00	65.61	14.02	0.76
Median	68.75	24.68	2.54	76.99	17.50	1.35	74.30	21.91	2.25
3rd Q	83.24	58.35	3.92	85.58	27.45	6.29	83.82	28.44	5.28
Max.	97.30	100.00	22.69	97.37	55.01	39.13	95.72	74.66	23.44
Mean	62.45	34.45	3.10	76.11	19.74	4.16	72.83	23.45	3.72
				Seed (%)					
	Fungicide	Herbicide	Insecticide	Fungicide	Herbicide	Insecticide	Fungicide	Herbicide	Insecticide
Min.	0.00	0.00	0.00	1.50	0.00	0.00	8.39	0.00	0.00
1st Q	21.93	12.62	18.36	28.61	13.07	13.77	27.91	15.56	18.11
Median	34.01	20.49	34.24	49.24	21.61	20.63	40.59	23.96	31.73
3rd Q	55.72	32.51	52.33	63.52	31.15	42.49	52.36	33.99	41.62
Max.	100.00	100.00	70.45	99.52	97.90	85.82	100.00	82.45	71.42
Mean	39.94	24.83	35.23	47.41	24.57	28.01	41.60	27.33	31.07

** Outliers not shown (points outside 1.5 times the interquartile range Q3 and below the Q1).*

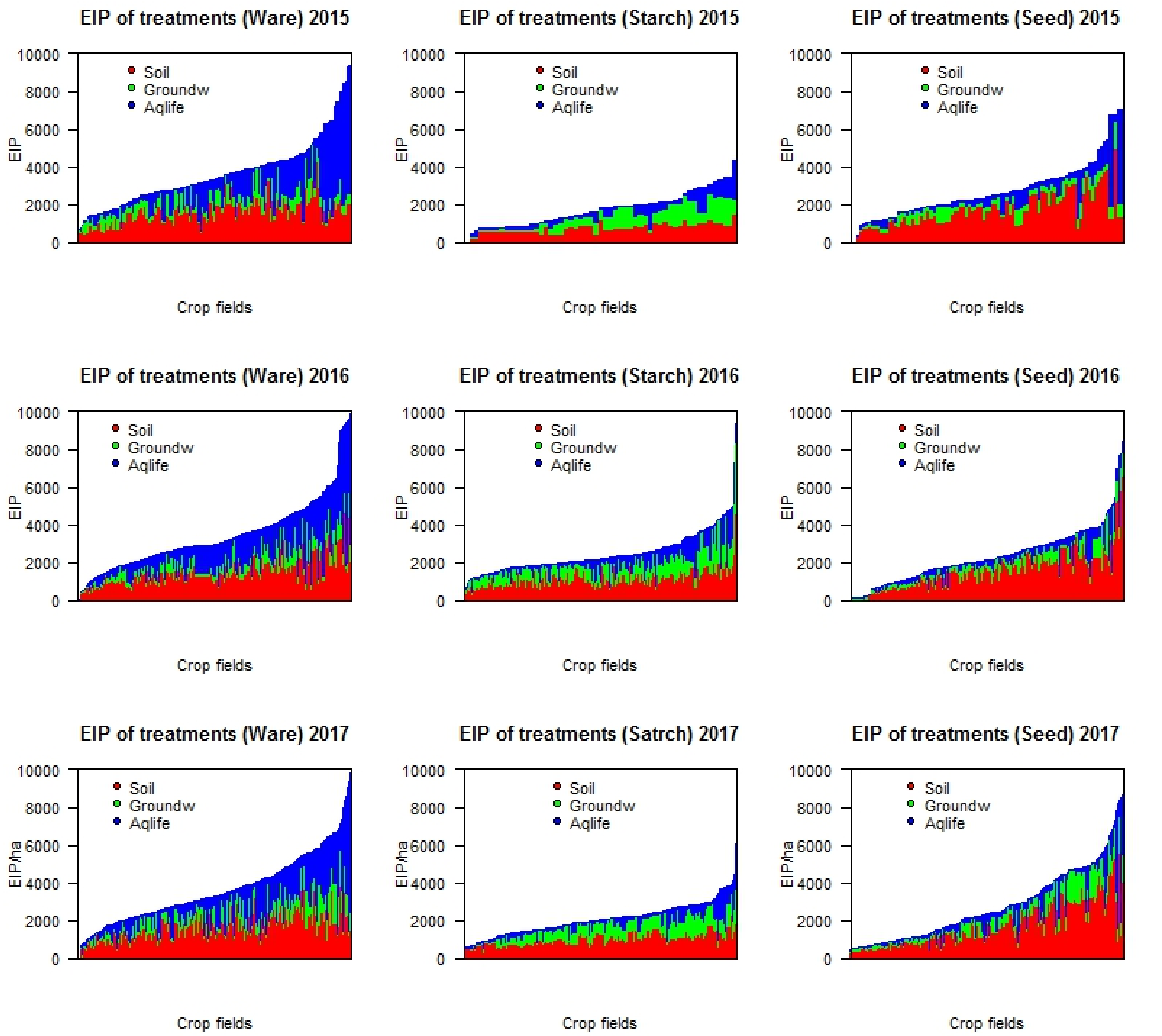

Figure E 1. Total environmental scores of pesticide treatments, divided by the environmental impact on soil life (red), ground water (green) and aquatic life (blue).
Presented by crop type (from left to right) and by year 2015 - 2017 (top-down). Each bar represents the values of EIP/ha of one individual potato field.

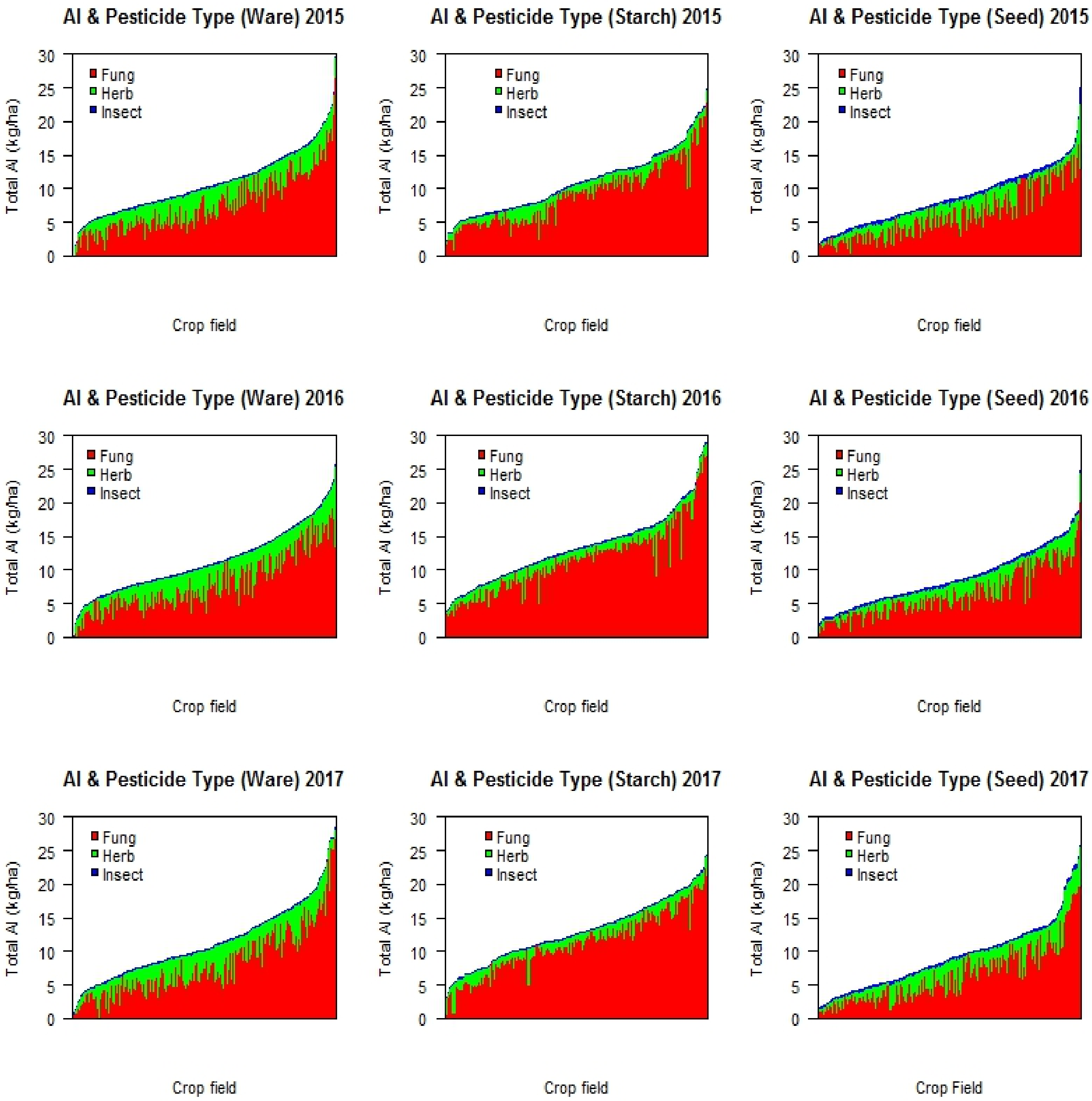

Figure E 2. Contribution of fungicides (red), insecticides (blue) and herbicides (green) to the total active ingredient (AI kg/ha) for each crop type (left to right) in years 2015 - 2017 (top-down).
Each bar represents the values of Total AI kg/ha in one individual potato field.

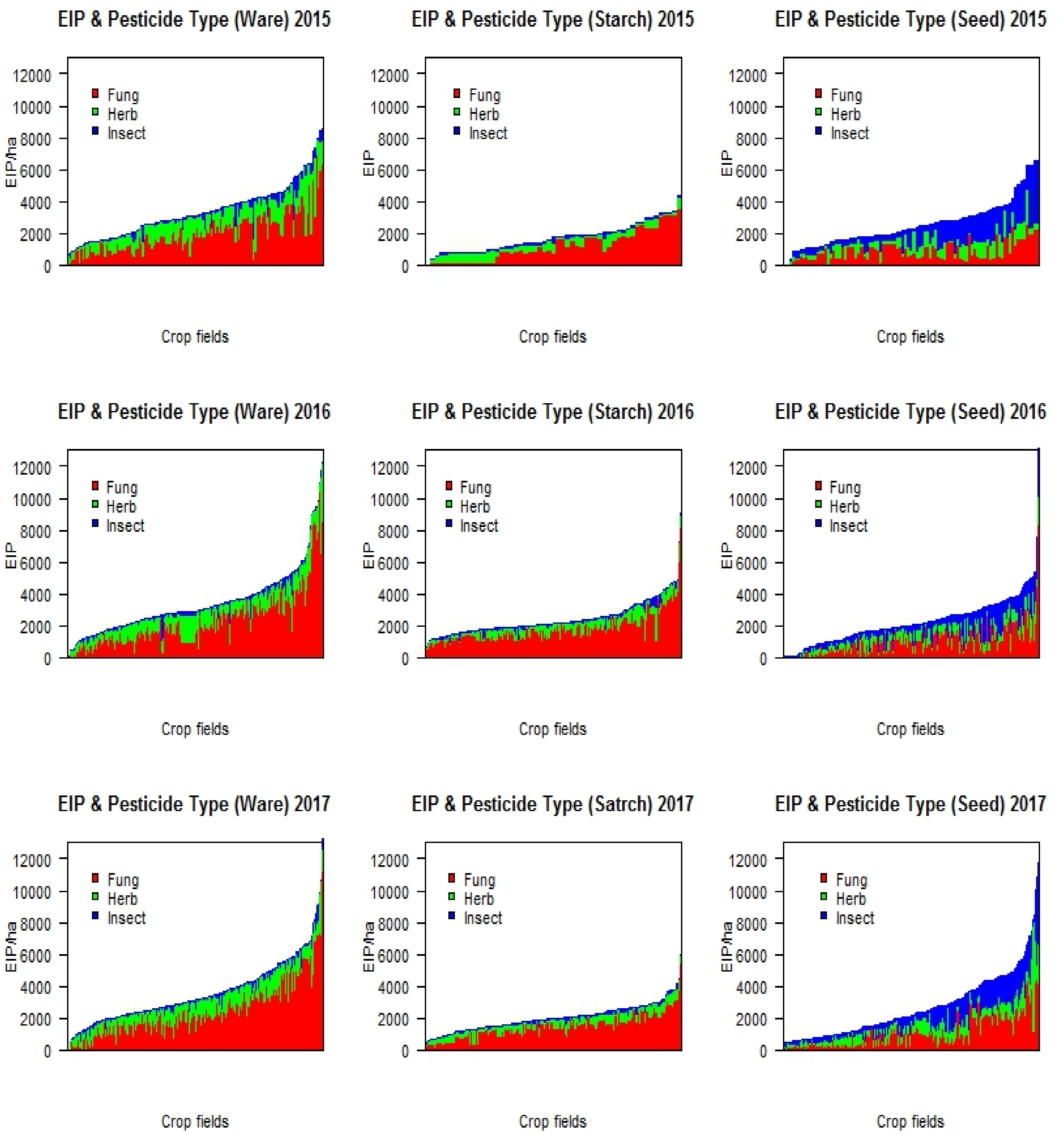

Figure E 3. Contribution of fungicides (red), insecticides (blue) and herbicides (green) to the environmental impact points (EIP/ha) for each crop type (left to right) in years 2015 - 2017 (top-down).
Each bar represents the values of EIP/ha in one individual potato field.

Table E 4. Mean values for yield (to/ha), total AI (AI kg/ha) and EIP per ha in low (Ylow), average (Yav) and high (Yhigh) yielding fields in 2017.

	Ware potato			Starch potato			Seed potato		
	Yield (ton/ha)	**AI** (kg/ha)	**EIP** (EIP/ha)	**Yield** (ton/ha)	**AI** (kg/ha)	**EIP** (EIP/ha)	**Yield** (ton/ha)	**AI** (kg/ha)	**EIP** (EIP/h)
Y*low*	38.2	8.7	2584	28.7	12.4	1906	26.9	10	1651
Y*av*	55.9	12.9	3811	46	12.1	1955	37.6	9.9	1954
Y*high*	69.2	13.9	3796	54.3	12.2	2132	52.4	13.5	2698