Impact of precision application of herbicides on leaching to groundwater

Mechteld ter Horst, Louise Wipfler, Koen van Boheemen, Jan Huijsmans

WAGENINGEN UNIVERSITY & RESEARCH

Impact of precision application of herbicides on leaching to groundwater

Mechteld ter Horst[1], Louise Wipfler[1], Koen van Boheemen[2], Jan Huijsmans[2]

1 Wageningen Environmental Research
2 Wageningen Plant Research

This research was (partly) subsidised by the Dutch Ministry of Agriculture, Nature and Food Quality (project number BO-43-102.01-013).

Wageningen Environmental Research
Wageningen, October 2023

Reviewed by:
Bastian Polst, Researcher (Wageningen Environmental Research

Approved for publication:
Sara Ahrari, teamleader of Environmental Risk Assessment

Report 3293
ISSN 1566-7197

Ter Horst, M.M.S., E.L. Wipfler, K. van Boheemen, J.F.M. Huijsmans, 2023. *Impact of precision application of herbicides on leaching to groundwater.* Wageningen, Wageningen Environmental Research, Report 3293. 46 pp.; 11 fig.; 9 tab.; 17 ref.

Momenteel wordt bij de beoordeling van uitspoeling van gewasbeschermingsmiddelen naar het grondwater als onderdeel van de registratieprocedure van deze middelen in de EU en Nederland geen rekening gehouden met precisietoepassingen. In dit rapport wordt een onderzoek naar de uitspoeling naar het grondwater van een herbicide toepast met een variabele dosering beschreven. Resultaten van modelsimulaties per behandeld vlak (10 x 24 m) in het perceel werden vergeleken met resultaten van een modelsimulatie op basis van een uniforme toepassing op het perceel. Voor de geselecteerde casus toonden de resultaten aan dat de gereduceerde (gemiddelde) dosering kan worden gebruikt bij de beoordeling van uitspoeling naar het grondwater voor stoffen met lineaire sorptie of een zwakke niet-lineariteit van sorptie. Voor stoffen met niet-lineaire sorptie zijn de verschillen tussen middeling van de dosering en middeling van de uitspoelconcentraties waarschijnlijk groter. Er zijn aanvullende stappen nodig om de resultaten van deze specifieke casus te extrapoleren naar de generieke beoordeling van uitspoeling naar het grondwater als onderdeel van de registratieprocedure van gewasbeschermingsmiddelen. In dit rapport wordt een vooruitblik gegeven op hoe dit zou gedaan zou kunnen worden. De verlaagde dosering zou probabilistisch kunnen worden afgeleid met behulp van meerdere voorbeeldcasussen met variabele dosering in het gebruiksgebied (Nederland) en bodeminformatie met een hoge ruimtelijke resolutie. De belangrijkste belemmering voor het afleiden van een dergelijke generieke benadering is, op dit moment, de beperkte beschikbaarheid van casussen van in de praktijk gebruikte beslismodellen voor het bepalen van een variabele dosering op basis van data van bodemscans.

Currently the leaching to groundwater assessment as part of the pesticide registration procedure in the EU and the Netherlands does not consider precision applications. This report describes a study on leaching to groundwater of a herbicide which is applied using a variable application technique. Model simulations per applied patch in the field were compared to those based on a full field application. For this selected case results showed that the reduced (averaged) dose can be used in the leaching assessment for substances with linear sorption or weak non-linearity of sorption. For non-linear sorbing substances the differences between averaging of the dose and averaging of the leaching concentrations are probably larger. To generalize these results to the generic leaching assessment applied in the regulatory context additional steps are needed. In this report an outlook is given on how this could be done. The reduced dose should be derived probabilistically while using multiple example cases with variable rate applications in the area of use (the Netherlands) and soil information at a high spatial resolution. The main obstacle to derive such a generic approach is the current limited availability of established dose-soil scan parameter relations.

Keywords: Precision application, leaching, PEARL model, groundwater, herbicide, soil, pesticides, plant protection product

The pdf file is free of charge and can be downloaded at https://doi.org/10.18174/640004 or via the website www.wur.nl/environmental-research (scroll down to Publications – Wageningen Environmental Research reports). Wageningen Environmental Research does not deliver printed versions of the Wageningen Environmental Research reports.

In 2003 Wageningen Environmental Research implemented the ISO 9001 certified quality management system.
Since 2006 Wageningen Environmental Research has been working with the ISO 14001 certified environmental care system.
By implementing the ISO 26000 guideline, Wageningen Environmental Research can manage and deliver its social responsibility.

Wageningen Environmental Research Report 3293 | ISSN 1566-7197

Photo cover: Editorial credit: Ivo Antonie de Rooij/Shutterstock.com

Contents

Verification

Report: 3293
Project number: BO-43-102.01-013

Wageningen Environmental Research (WENR) values the quality of our end products greatly. A review of the reports on scientific quality by a reviewer is a standard part of our quality policy.

Approved reviewer who stated the appraisal,

position: Researcher

name: Bastian Polst

date: 2 October 2023

Approved team leader responsible for the contents,

name: Sara Ahrari

date: 16 October 2023

Preface

The Implementation Programme for the Vision for the Future of Plant Protection put forward by the Ministry of Agriculture, Nature and Food Quality aims at the adoption of sustainable production methods, with resilient plants and cultivation systems, so that diseases and pests have far less chance of taking hold, and the use of plant protection products is reduced to a minimum.

One of the options that facilitate the realisation of resilient cultivation systems are technical measures. Technical measures can be used to prevent diseases, pests and weeds and to contain and control them (location, plant and time-specific). These technical measures include precision technologies designed to achieve a reduction in the amount of plant protection product (PPP) applied (e.g. variable rate applications).

Current environmental risk assessments (e.g. the leaching to groundwater assessment) as part of the pesticide registration procedure in the EU and the Netherlands, do not take precision applications into account. For these assessments homogenous pesticides applications according to the advised dose (full field applications) are assumed. Precision applications could be considered as one of the mitigation options in the risk assessment. However, there is currently a lack of information on the impact of such precision applications on the environment.

This report describes a study in which the impact of precision applications of herbicides on leaching to groundwater was investigated and compared to full field applications.

This study was conducted by Wageningen Environmental Research (WENR) in cooperation with Wageningen Plant Research (WPR) in the research theme BO-43 – Sustainable Food Supply and Production & Nature – Sustainable Crop Protection, project BO-43-102.01.013 funded by the Dutch Ministry of Agriculture, Nature and Food Quality.

Summary

In the Implementation Programme for the Vision for the Future of Plant Protection put forward by the Ministry of Agriculture, Nature and Food Quality several technical measures are mentioned that facilitate the realisation of resilient cultivation systems. These measures can be used to prevent diseases, pests and weeds and to contain and control them (location, plant and time-specific). One of these technical measures is the use of precision technologies designed to achieve a reduction in the amount of Plant Protection Product (PPP) applied (e.g. variable rate applications).

Van Boheemen et al. (2022) define a precision-application of Plant Protection Products (PPPs) as an application for which site-specific measurements are done and a site-specific decision is made and for which this decision is subsequently carried out site-specifically.

Currently the environmental risk assessments (e.g. the leaching to groundwater assessment) which are conducted as part of the pesticide registration procedure in the EU and the Netherlands, do not take precision applications into account. For these assessments homogenous pesticides applications according the advised dose are assumed. Given that precision applications lead to a lower use of PPPs they could potentially be considered as one of the mitigation options in the risk assessment. However there is currently a lack of information on the impact of such precision applications on environmental risks as compared to conventional applications.

In this report we describe a study in which the impact of a variable rate application of a herbicide on leaching to groundwater was investigated and compared to full field applications.

In case of variable rate applications, a straight forward approach to assess the groundwater concentration could be to use the average reduced dose as applied over the entire field. This is defensible if processes (e.g. sorption to soil organic matter) are linearly dependent of the concentration in soil. However, for non-linear processes an average applied dose may give a different concentration in the groundwater than the average of a series of different dose applications applied per patch in the field.

Via simulations with the PEARL model and using the case study of a field of seed onions treated with variable rate applications of a herbicide product we assessed the impact of averaging of the dose on the calculated concentration in groundwater at 1 m depth as compared to the average concentration which results from variable-dose applications. This was done by comparing the concentrations in groundwater at 1 m depth as result of two model simulations using reduced pesticide doses (61.5% and 65.5% reduction in applied PPP related to the advised dose) with the area weighted average concentration in groundwater at 1 m depth of a series of model simulations for all patches in the field with variable rate applications.

For this case study using the reduced doses resulted in concentrations that are *different from* the area weighted average concentration from the simulations with variable rate applications. The difference is however small due to the rather weak non-linearity of the sorption of the substance used in simulations. Substances with stronger non-linear sorption might show larger differences between the two types of assessments.

Given the outcome of the simulations, it could be defensible for substances with weak non-linearity of sorption to use a reduced dose for a particular PPP as result of precision application techniques in the leaching to groundwater assessment for regulatory purposes. However, the achieved reduced dose for a particular PPP depends on the local conditions during application. This means that using the reduced dose of one specific case in the leaching assessment does not necessarily lead to a leaching endpoint that is protective for all other possible situations. To extrapolate the results of this study to the generic leaching assessment applied in the regulatory context additional steps are needed. The reduced dose could be derived probabilistically using multiple example cases with variable rate applications in the area of use

(the Netherlands) and soil information at a high spatial resolution. The main obstacle to derive such a generic approach is the current limited availability of established dose-soil scan parameter relations (i.e. decision-making models for variable rate applications of soil herbicides based on soil scans).

Samenvatting

In het Uitvoeringsprogramma Toekomstvisie Gewasbescherming 2030, voorgesteld door het Ministerie van Landbouw, Natuur en Voedselkwaliteit, worden verschillende technische maatregelen genoemd als opties die veerkrachtige teeltsystemen mogelijk maken, omdat ze kunnen worden gebruikt om ziekten, plagen en onkruiden te voorkomen en daar waar nodig te beheersen en te bestrijden. (locatie-, plant- en tijdspecifiek). Eén van de technische maatregelen zijn precisietechnologieën, ontworpen om een reductie in de hoeveelheid gewasbeschermingsmiddel toe te passen (bijvoorbeeld variabele toepassingen, waarbij de dosering per locatie in het veld wordt aangepast).

Van Boohemen et al. (2022) definiëren precisietoepassingen van gewasbeschermingsmiddelen als een toepassing waarbij er plaats specifieke metingen worden verricht én er een plaats specifieke beslissing wordt genomen én waarop vervolgens deze plaats specifieke beslissing wordt uitgevoerd.

Op dit moment houden de milieurisicobeoordelingen (bijvoorbeeld de beoordeling van uitspoeling naar grondwater) als onderdeel van de registratie procedure voor gewasbeschermingsmiddelen in de EU en Nederland geen rekening met precisietoepassingen. Voor deze beoordelingen worden homogene toepassingen volgens de geadviseerde dosis verondersteld. Precisietoepassingen zouden kunnen worden beschouwd als één van de mitigatie-opties in de risicobeoordeling. Er is echter momenteel een gebrek aan informatie over de impact van dergelijke precisietoepassingen op het milieu.

In dit rapport beschrijven we een studie waarin de impact van een variabele toepassing van een herbicide op de uitspoeling naar grondwater werd onderzocht.

Een eenvoudige benadering die gebruikt kan worden in de beoordeling van risico's voor het grondwater is het gebruiken van de veld gemiddelde gereduceerde dosering voor berekenen van de grondwaterconcentratie. Dit is verdedigbaar voor stoffen waarvoor processen (bijvoorbeeld adsorptie aan bodemorganische stof) lineair afhankelijk zijn van de concentratie in de bodem. Voor niet-lineaire processen kan een veldgemiddelde toegepaste dosering echter een andere concentratie in het grondwater geven dan het gemiddelde van een reeks toepassingen met een plaats specifieke dosering.

Om de impact op de berekende concentratie in het grondwater op 1 m diepte te beoordelen van enerzijds gebruik van de veld gemiddelde, gereduceerde dosering en anderzijds de variabele toepassingen, zijn er simulaties met het PEARL model uitgevoerd. Berekeningen zijn gedaan voor een case studie van behandeling van een veld met zaaiuien via een variabele toepassing van een herbicide product.

De concentratie in het grondwater op 1 m diepte als resultaat van twee modelsimulaties met veld gemiddelde doseringen (61,5% en 65,5% reductie ten opzichte van de adviesdosering) zijn vergeleken met de oppervlakte gewogen gemiddelde grondwater concentraties van een reeks van model simulaties voor alle situaties in het veld met variabele toepassingen.

Voor deze case studie resulteerde het gebruik van de veld gemiddelde, gereduceerde doseringen in andere berekende grondwater concentraties dan de oppervlakte gewogen gemiddelde grondwater concentratie van de model simulaties met variabele toepassingen. Het verschil is echter klein vanwege de vrij zwakke niet-lineariteit van de sorptie van de stof die in de simulaties is gebruikt. Stoffen met een sterkere niet-lineariteit van sorptie kunnen grotere verschillen vertonen tussen de twee soorten concentraties.

Voor de registratie van gewasbeschermingsmiddelen zou het, gezien de uitkomst van de simulaties, voor stoffen met een zwakke niet-lineariteit van sorptie verdedigbaar kunnen zijn om de veld gemiddelde, gereduceerde dosering te gebruiken voor de risicobeoordeling van uitspoeling naar het grondwater. De met een precisietechniek tot stand gekomen gereduceerd dosering van een specifiek gewasbeschermingsmiddel hangt echter af van de lokale omstandigheden tijdens de toepassing. Dit betekent dat gebruik van de tot

stand gekomen gereduceerd dosering van één specifiek geval in de beoordeling van uitspoeling naar grondwater niet noodzakelijkerwijs resulteert in een eindpunt voor de risicobeoordeling dat beschermend is voor alle andere mogelijke situaties. Er zijn additionele stappen nodig om de resultaten van deze studie te kunnen extrapoleren naar de generieke beoordeling van uitspoeling van gewasbeschermingsmiddelen naar het grondwater. De gereduceerde dosering zou probabilistisch kunnen worden bepaald aan de hand van meerdere voorbeeldgevallen met variabele toepassing in het gebruiksgebied (Nederland) en bodeminformatie met een hoge ruimtelijke resolutie. De belangrijkste belemmering voor het ontwikkelen van zo’n generieke aanpak is momenteel de beperkte beschikbaarheid van in de praktijk toegepaste doseermodellen op basis van bodemscans.

1 Introduction

Precision techniques are increasingly used to increase the effect and efficiency of Plant Protection Products (PPPs) and lower the total mass of PPPs applied to a field. Currently, mostly herbicides are applied with precision techniques. We refer to Boheemen et al. (2022) for an overview of precision technique options to apply PPPs. Based on sensor information of (in-field) spatially variable soil or cropping conditions, application of PPP is optimised; i.e. site-specific conditions within the treated field are measured and the corresponding specific minimum effective dose is derived and applied, leading to non-uniform application of PPPs in a treated field. Currently, most commonly used machines capable of variable applications can apply only a single dose over the entire working width (Boheemen et al. 2022). This means that patches of uniform application often depend on the working width of the boom sprayer, which generally varies between 24 and 50 m and the distance after which the dose can be adapted; currently every 1 to 2 m[1]. The total applied dose per field is inherently lower than when applied with conventional application techniques.

For the environmental risk assessments as part of the pesticide registration procedure in the EU and the Netherlands, homogenous pesticide application according the advised dose is assumed. No guidance is available on how to assess spot spraying and variable rate herbicide applications or a combinations of these two (hybride) in the current evaluation methods. A reasonable option would be to include precision applications as one of the mitigation options to be considered in the risk assessment.

In the groundwater risk assessment the overall 90th percentile groundwater concentration at 1 m depth below a treated field is calculated, i.e. the field is the spatial unit for which the risk is assessed. In case of variable rate applications, a straight forward approach to assess the groundwater concentration could be to use the average reduced dose (e.g. the average of the specific minimum effective dose) as applied over the entire field. This is defensible for fate processes in the soil such as transport, degradation, sorption that are linearly dependent of concentration. However, for non-linear processes an average applied dose may give a different concentration in the groundwater than the average of a series of different dose applications applied per patch in the field.

In this study the impact of averaging of the dose is assessed on the calculated groundwater concentration at 1 m depth as compared to the average concentration which results from variable-dose applications. The spatial scale considered is the (applied) field.

For clarity the most important definitions used in this report are provided in Table 1.

[1] In the forthcoming years patches of uniform applications of 0.25x0.25 m^2 or 0.50x0.50 m^2 will become more common as the latest generation of sprayers can be equipped with a system that is capable of varying the dose per nozzle.

Table 1 *Key definitions used in this report (based on van Boheemen et al., 2022).*

Minimum effective dose	Definition according EPPO standard PP1/225(2): The dose that is the minimum necessary to achieve sufficient efficacy against a target pest across the broad range of situations in which the product will be applied.
Specific minimum effective dose	EPPO standard PP1/225(2) states the following: Where the product is proposed for use under diverse conditions, there may be situations that warrant the use of different doses, for example, in situations with different cropping practices or crop structures, or variation in the inherent sensitivity of the target pest. Thus for a specific target, it may be possible to justify a number of specific 'minimum effective doses' under defined conditions. We introduce here the definition term 'specific minimum effective dose' to refer to the dose that is theoretically just high enough for the product to be effective under the given specific conditions. The specific minimum effective dose depends on several factors and can be calculated (approximated) using decision models if these models are available for the PPP in question.
Advised dose	The dose recommended by the manufacturer of the PPP and specified on the legal instructions of use as evaluated and laid down by the competent registration authority. Application of a larger dose than the advised dose is not permitted.
Application dose	The dose which is sent to the sprayer for application. The systems on the sprayer will try and achieve this dose by controlling the flow per second. The application dose is not necessarily equal to the specific minimum effective dose. As explained in van Boheemen et al. (2022), the specific minimum effective dose can be calculated for different measuring points underneath the working width of the boom sprayer. However, in a final step, these different specific minimum effective doses are converted to a single application dose applied uniformly over the working width of the boom sprayer.
Applied dose	Applied dose is the dose actually applied by the sprayer. The applied dose can differ from the application dose due to (technical) limitations of the sprayer. If the situation in the field requires large differences in application dose in areas located directly besides each other, the sprayer could need time to adjust the application rate resulting in differences between the application dose and the applied dose.
Spot spraying applications	The PPP is only applied in areas where application is required.
Variable rate applications	Variable rate applications are defined as applications for which the application rate is adjusted based on site specific situations; i.e. the entire area of the field is sprayed, but the application is not constant within a field.
Average of the minimum effective dose	The area weighted average of all specific minimum effective doses calculated per location in an agricultural field.

2 Case study: Variable rate applications of (soil) herbicide Wing-P

This case study is described in the report of van Boheemen et al. (2022). Note that this is a realistic example, i.e. we used the variable rate applications of a task map (Figure 4) used by a farmer to apply a soil herbicide. Variable rate applications of soil herbicide Wing-P were used to control weeds after the sowing of seed onions on a 8.3 ha field with sandy soils in 2019. A soil organic matter map was made based on measurements of the average organic matter content of the top 30 cm of the soil by the soil scanner Veris MSP-3 (Figure 2).

The advised dose of Wing-P for use after sowing of seed onions is 4.0 L product/ha (1 application per year) (Ctgb, Authorized products database, visited on 16 September 2021).

A decision-support model, based on the average soil organic matter map content in the top 30 cm, was used to calculate the specific minimum effective dose for each location in the field (Kempenaar et al., 2013). The spatial resolution is indicated in Figure 3. The model used is provided by FarmMaps[2] as specified below:

$$Dose_{(min,max)} = a \cdot OM + b \qquad \text{Eq. 1}$$

Dose is the dose of the product in L/ha, OM is the average soil organic matter content in the top 30 cm (%) and a and b (L/ha) are empirical parameters defining the position and slope of the linear relationship.

Rationale behind the model is that spots in the field with lower organic matter content need a lower dose as less pesticide is adsorbed to the organic matter and thus remains active in controlling weeds. The model of Eq. 1 uses minimum and maximum dosages. These are determined by the application technique, the local conditions (e.g. pest pressure) and the legal framework. In particular the maximum is limited by the authorization conditions (i.e. the advised dose). Values of the minimum, maximum and parameters a and b are pesticide product specific and based on experiments, literature research and knowledge and experiences from practical situations (Kempenaar et al., 2013).

Figure 1 gives a schematic representation of a hypothetical decision making model for variable rate applications. The green line represents the minimum effective dose (see definition listed in Table 1). Applying doses lower than the minimum effective dose are undesirable because of e.g. pest populations becoming resistant to pesticides. The blue line represents the part where the linear relationship between the dose and the soil scan parameter has been validated (e.g. the linear relationship of Eq. 1). The red line represents the maximum dose which is amongst others determined by the pest pressure and farmers experiences from crop protection practices that worked in the past, but is limited by the authorization conditions (i.e. the advised dose). The relationship derived for this case study is not only unique for the pesticide product, but also for the field and the local circumstances at the field around the time of application of Wing-P.

[2] https://www.farmmaps.net/en/Apps/Application/VRA-Soil-Herbicide (Website last entered on 10 October 2023).

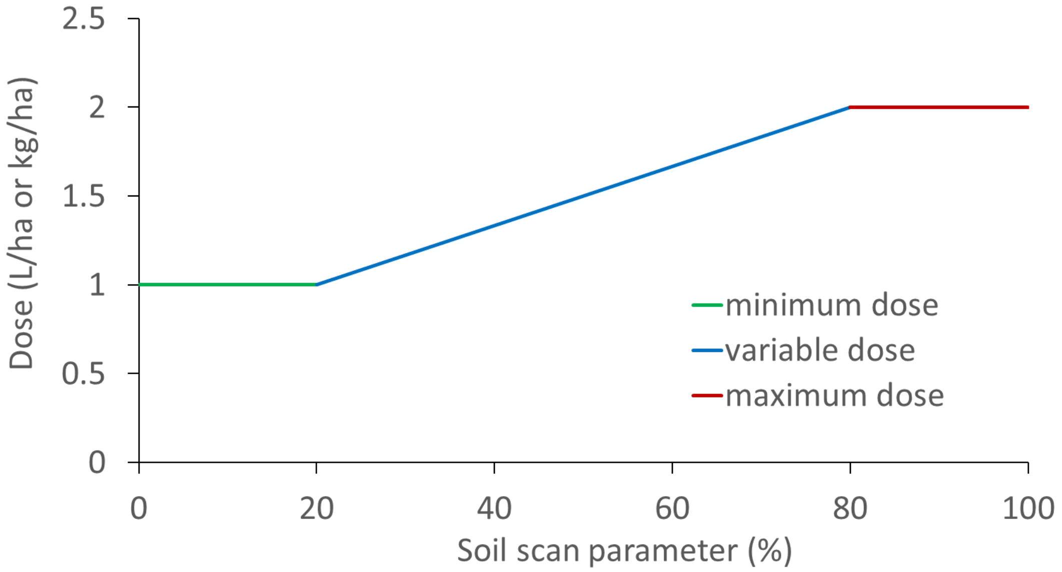

Figure 1 *Schematic representation of the decision-making model for variable rate applications of soil herbicides based on soil scans. The soil scan parameter i.e. organic matter content. The scale of the x-axis is however relative in this figure, i.e. zero to 100%.*

Figure 2 shows the soil organic matter map of the treated field of the case study based on measurements by the soil scanner Veris MSP-3. Figure 3 provides a map of the specific minimum effective dose calculated for the different locations in the field using Eq. 1 and the organic matter map of Figure 2. Based on Figure 3 the average of the specific minimum effective dose is calculated to be 1.38 L (product)/ha with a maximum of 1.54 L/ha and a minimum of 1.13 L/ha. Figure 3 is further converted into a task map which is needed to practically apply the application with a 24 m working width boom sprayer (Figure 4). Figure 4 shows the spraying volume in L/ha (note that 400 L/h spraying volume equals 1.4 L product/ha) on patches of 10x24 m^2. The spraying volume of these patches in calculated based on the average dose of product for each patch (see Figure 1 in van Boheemen et al., 2022 for more detailed information).

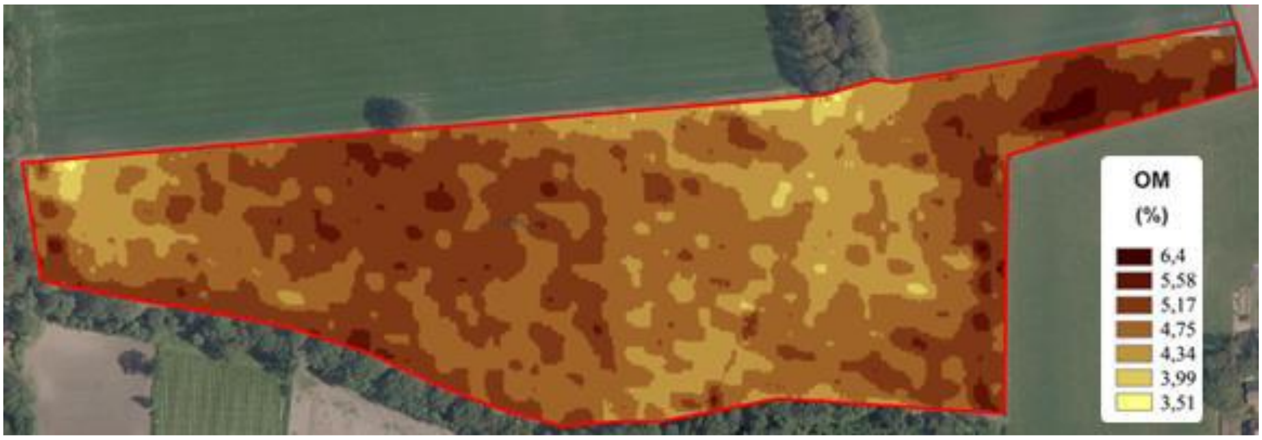

Figure 2 *Soil organic matter map of the treated field of the case study based on measurements by the soil scanner Veris MSP-3. Note that the average soil organic matter content in the top 30 cm of the soil is provided. Figure taken from van Boheemen et al. (2022).*

Figure 3 *Map of treated field showing the specific minimum effective doses of Wing-P (L/ha) calculated for the different locations in the field. Figure taken from van Boheemen et al. (2022).*

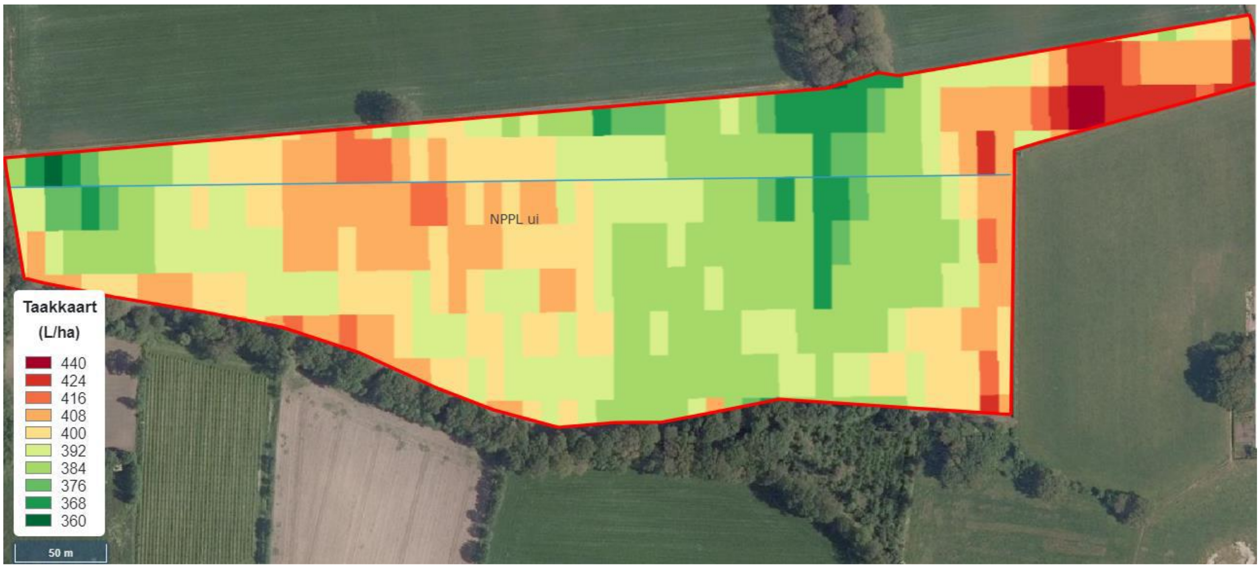

Figure 4 *Task map of the treated field showing the spraying volume (L/ha; Note 400 L/h spraying volume equals 1.4 L product/ha) adjusted to a 24 m working width boom sprayer. Figure taken from van Boheemen et al. (2022).*

The task map of Figure 4 was used by the farmer to apply Wing-P (see Annex 1 for data on the spray volume and product dose). The actual applied dose applied on the field however, might deviate somewhat from the task map (see also the definition of 'Applied dose' in Table 1). An as-applied map[3] showing the actually applied dosages was not available for this case. Unfortunately, the decision support model (i.e. values of parameters a and b in Eq. 1) used for this specific Wing-P case was also not available. Therefore, the task map and its underlying data, which was kindly provided by Koen van Boheemen (WPR), was used to calculate the dose of Wing-P for each patch (10x24 m^2) in the field (see also Annex 1).

[3] Most precision agriculture machines have the ability to produce an as-applied map. This as-applied map indicates how the task-map was actually applied; i.e. it contains site-specific information about the location and PPP dosage applied.

3 Simulations of leaching to groundwater

3.1 Modelling approach

Simulating the hydrology at the time of application in the actual field of the Wing-P case in the SWAP model (i.e. the soil-hydrological model underlying the PEARL model; Van den Berg et al. 2016) is a time consuming and complex task. Data on e.g. soil properties, groundwater levels, crop growth and meteorology are needed to parameterise the model. Once the model is parameterised for the respective field, calibration using e.g. data of measured groundwater levels might be needed to fine tune some of the model parameters such that the parameterisation provides a good description of the hydrological behaviour. Therefore and because we are only interested in the difference in leaching concentration between one simulation using an average dose and a series of simulations with variable dosing, we use an alternative approach, taking a parameterised well-known field and add variable dosing taken from the case study.

The variable dose in the case study is based on OM only, i.e. the higher the OM the higher the dosing (Eq. 1). Next to dosing, OM also affects leaching of substances to groundwater (e.g. Boesten and van der Linden, 1991). Therefore, we decided to include the in-field variability of OM in the leaching calculations. This implies that we assess the impact of variable dosing, while including the additional feedback from the OM towards the leaching.

Concretely, it was decided to use the FOCUS Groundwater Kremsmünster scenario (FOCUS, 2000) as the basis for the analysis. This scenario is officially adopted in the Netherlands as the first tier in the groundwater assessment. The only adaption made to the scenario is that the soil organic matter content of the top 30 cm of the soil of this scenario was replaced by the soil organic matter content measured at the field. The Kremsmünster scenario has a relatively low organic matter content as compared to the treated field, i.e. 3.6%. Organic matter content in the upper 30 cm of the field of the case study varies between 3.5 and 6%[4]. The soil properties dry bulk density and porosity are correlated to mass organic matter fractions. These have a much lower impact on PPP leaching and were kept constant (i.e. equal to the Kremsmünster scenario) for convenience.

The Kremsmünster onions scenario (FOCUS, 2000) was used. The crop development in this scenario is simulated assuming crop emergence at 25 April and harvest on 1 September. This is fairly analogous to the crop development of onions in the Netherlands.

The selected application date of Wing-P is 6 May (11 days after emergence of onions in the Kremsmünster onions scenario). The exact date of emergence of the crop in the case study is unknown. It is likely that the date of crop emergence is not exactly the same in the field case and the Kremsmünster onions scenario.

Wing-P contains two active ingredients: pendimethalin (250 g a.i./L product) and dimethenamid-P (212.5 g a.i./L product). Pendimethalin has a high sorption coefficient, i.e. 8000 L/kg and dimethenamid-P has a much lower sorption coefficient, i.e. 66 L/kg. Indicative simulations using the Kremsmünster onions scenario (incl. its organic matter content) and the advised dose (4.0 L product/ha) showed that pendimethalin with its high sorption coefficient resulted in zero annual leaching concentrations whereas simulations for dimethenamid-P showed annual leaching concentrations ranging from 0.0 to 0.01 µg/L due to the lower sorption coefficient of dimethenamid-P. Although leaching concentrations are still low it was decided to focus the modelling exercise on dimethenamid-P.

---

[4] The Kremsmünster scenario assumes an organic matter content of 0.5% for the layer 30-50 cm and 0.1% for the soil below 50 cm depth. At the field of the case study organic matter contents are not measured for soil layers deeper than 30 cm. The soil at the field of the case study is classified as sandy soil (lutum (<2µm) < 10%) for which organic matter contents in the subsoil are generally between 0-3% in the Netherlands (Heinen et al., 2020). Given that at the field of the case study the organic matter content of the upper 30 cm is measured to be between 3.5% and 6%, it seems reasonable to assume that at the field of the case study the organic matter contents of the soil below 30 cm the organic matter contents are higher than the organic matter contents of the soil below 30 cm of the Kremsmünster scenario.

In addition, we did a simulation with the sorption coefficient set to 1.0 L/kg and a Freundlich coefficient set to 1.0 (minimal and linear sorption) to 1) enlarge the leached mass to groundwater and to 2) verify that in case of linear sorption averaging of the dose gives a concentration in the groundwater that is similar to the average of a series of different dose applications applied per patch in the field. Note that substance properties are provided in Annex 2.

PEARL simulations were done for each patch in the field of the case study with a particular combination of the dose and measured organic matter content (see Annex 1).

For each patch, the dose of dimethenamid-P was calculated based on the information that 400 L/ha of spraying volume equals 1.4 L product/ha (personal communication Koen van Boheemen, WPR) and that the concentration of dimethenamid-P in Wing-P is 212.5 g a.i./L product (Ctgb, authorized products database; visited on 16 September 2021).

Figure 5 provides the relationship between the mass organic matter fraction and the dose of dimethenamid-P as used for the simulations with PEARL and according to the data (Van Boheemen et al., 2022).

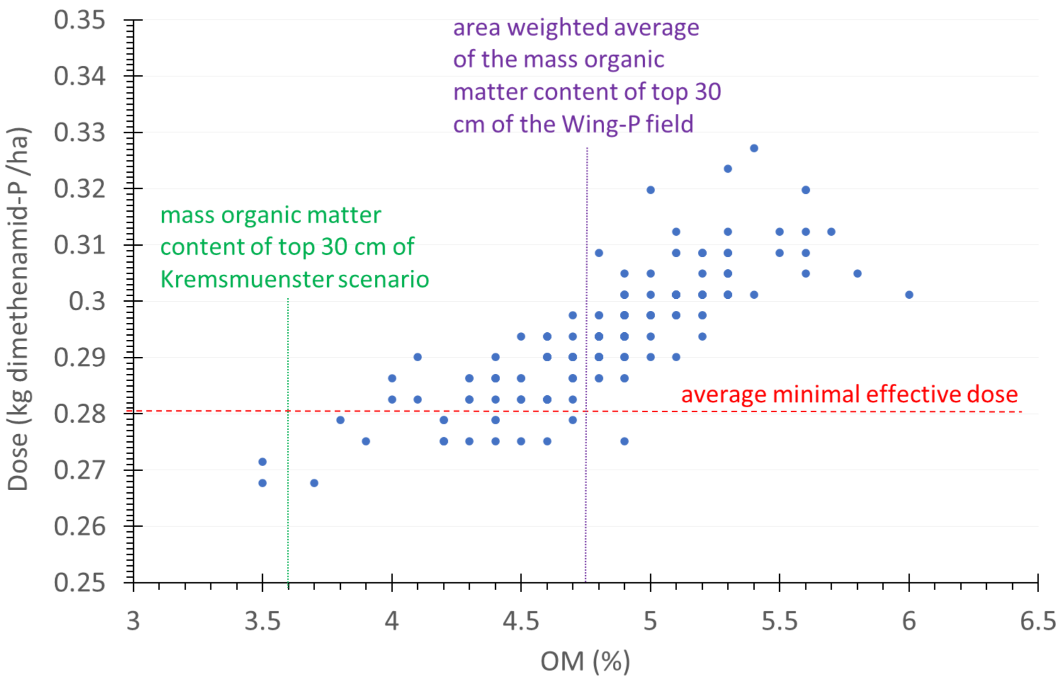

Figure 5 *Relationship between the mass organic matter fraction and the dose dimethenamid-P as used for the simulations with PEARL. The relationship is based on data of the 164 patches of the Wing-P field. Note that some of the dots represent more than 1 patch. The dotted green line indicates the mass organic matter fraction of the top 30 cm of the Kremsmünster scenario and the red dashed line indicates the average of the specific minimum effective dose (i.e. a 65.5% reduction in applied PPP related to the advised dose).*

The 80th (temporal) percentile leaching concentration was extracted from the PEARL output. This is the endpoint in the leaching assessment and represents the overall 90th percentile concentration (in time and space)[5]. Each simulation was done per dot in the graph shown in Figure 5. Based on the area that this simulation represented in the field the area weighted average leaching concentration was derived.

[5] FOCUS (2000) decided that the overall vulnerability approximating the 90th percentile of all possible situations could be best approximated by using a 80th percentile value for soil and a 80th percentile value for weather. The 80th percentile for weather was determined by performing simulations using multi-year weather data (so a temporal percentile), while the 80th percentile soil was selected by expert judgement (a spatial percentile). Latest scientific insights however show that the overall vulnerability approximating the 90th percentile of all possible situations is better estimated by a 90th percentile in time and a 90th percentile in space (see e.g. Appendix A in Adriaanse et al., 2022).

Two sets of simulations were done:

1. Using values of the sorption coefficient (Kom_{soil} = 66.12 L/kg) and the Freundlich coefficient (N = 0.965) as reported in the EFSA conclusion of dimethenamid-P (EFSA, 2005; see Annex 2).
2. Using a sorption coefficient, Kom_{soil}, of 1.0 L/kg (mobile to highly mobile) and assuming linear sorption (Freundlich coefficient, N, of 1.0).

The results of these two sets of simulations with variable rate applications were compared to the following PEARL simulations with the Kremsmünster onion scenario using:

A. The advised dose i.e. 4 L Wing-P/ha, so 0.85 kg a.i./ha.
B. The highest dose calculated from the task map, i.e. 1.54 L Wing-P/ha (61.5% reduction in applied pesticide product related to the advised dose), so 0.3273 kg a.i./ha.
C. The average of the specific minimum effective dose i.e. 1.38 L Wing-P/ha (65.5% reduction in applied pesticide product related to the advised dose), so 0.2933 kg a.i./ha[6].

PEARL simulations for A, B, and C, were done in two-fold using i. the area weighted average of the mass organic matter content of the field of the case study (4.74% for the top 30 cm) and ii. the mass organic matter content of the scenario (3.6% for the top 30 cm). Resulting in 6 PEARL simulations (cases 2-7 in Table 2). For all simulations one application 11 days after emergence was assumed.

An overview of all simulations done with the PEARL model is given in Table 2.

Table 2 *Overview of simulations done with the PEARL model.*

Substance properties	Case nr	Type dose (kg a.i./ha)	Organic matter content of top 30 cm (%)	Application
set 1 Kom_{soil} = 66.12 L/kg and N = 0.965	1	Variable: 164 patches	Variable in line with Wing-P field	one application 11 days after emergence
	2	0.85 (A: advised dose)	4.74	
	3	0.3273 (B: 61.5% reduction)	4.74	
	4	0.2933 (C: 65.5% reduction)	4.74	
	5	0.85 (A: advised dose)	3.6	
	6	0.3273 (B: 61.5% reduction)	3.6	
	7	0.2933 (C: 65.5% reduction)	3.6	
set 2 Kom_{soil} = 1.0 L/kg and N = 1.0	1	Variable: 164 patches	Variable in line with Wing-P field	one application 11 days after emergence
	2	0.85 (A: advised dose)	4.74	
	3	0.3273 (B: 61.5% reduction)	4.74	
	4	0.2933 (C: 65.5% reduction)	4.74	
	5	0.85 (A: advised dose)	3.6	
	6	0.3273 (B: 61.5% reduction)	3.6	
	7	0.2933 (C: 65.5% reduction)	3.6	

In order to test the hypothesis that the concentrations are **not** averaged out over the field, for substances with non-linear sorption. The results of case 1 are compared to those of case 2, 3 and 4 for both sets of substance properties.

Furthermore, the results of cases 5, 6 and 7 are compared to the results of case 1. The reason for this comparison is to learn the protectiveness of the Tier 1 leaching assessment for national PPP registration in the Netherlands (Van der Linden et al., 2004) using the advised dose and the reduced doses, for this particular Wing-P case.

[6] Note that the PEARL simulations for C were done with the unrounded value of the area weighted average of the doses provided in Annex 1 (i.e. 1.3774 L Wing-P/ha and thus 0.2927 kg a.i./ha).

3.2 Results

Annex 3 provides the leaching concentrations for each of the two sets of simulations with variable rate applications of Wing-P. As expected, the leaching concentrations are much higher for Set 2 (Kom_{soil} = 1 L/kg and N = 1) than for Set 1 (Kom_{soil} = 66.12 L/kg and N = 0.965) because sorption is negligible for Set 2. Note that for both sets the leaching concentrations are below the precautionary quality standard of 0.1 µg /L.

Table 3 presents the area weighted average of the endpoints of the 164 simulations (case 1). The area weighted average of the 80th percentile leaching concentration was calculated as follows using the area of each patch as weighting factor:

$$Area\ weighted\ average\ of\ 80th\ perc.\ leaching\ concentration = \sum_{n=1}^{164} \frac{A_n \cdot c_n}{A_{field}} \qquad Eq.\ 2$$

Where n is the patch number, A_n is the area of patch n, c_n is the 80th percentile leaching concentration calculated for patch n, and A_{field} is the total area of the field of the case study (83381.34 m^2).

Table 3 *Results from the PEARL simulations for 164 patches using the dose and mass organic matter content as specified in Annex 1.*

Case Nr.	Substance properties set	Area weighted average of the 80th percentile leaching concentration (µg/L)
1	Set 1: Kom_{soil} = 66.12 L/kg and N = 0.965	2.47E-04
1	Set 2: Kom_{soil} = 1 L/kg; N = 1	2.194

Table 4 and Table 5 show the 80th percentile leaching concentrations of cases 2 up to and including 7 for respectively substance properties sets 1 and 2.

Table 4 *Results of simulations with FOCUS PEARL 5.5.5. with the Kremsmünster onion scenario for set 1: using Kom_{soil} = 66.12 L/kg and N = 0.965 and different doses: the advised dose, the highest dose calculated from the task map (61.5% reduction in applied PPP related to the advised dose) and the average of the specific minimum effective dose (65.5% reduction in applied PPP related to the advised dose).*

Case Nr.	Type dose (kg a.i./ha)	Organic matter content of top 30 cm (%)	80th percentile leaching concentration (µg/L)
2	0.85 (A: advised dose)	4.74	8.43E-04
3	0.3273 (B: 61.5% reduction)	4.74	2.59E-04
4	0.2933 (C: 65.5% reduction)	4.74	2.25E-04
5	0.85 (A: advised dose)	3.6	2.69E-03
6	0.3273 (B: 61.5% reduction)	3.6	8.66E-04
7	0.2933 (C: 65.5% reduction)	3.6	7.59E-04

Table 5 *Results of three simulations with FOCUS PEARL 5.5.5. with the Kremsmünster onion scenario for set 2: using Kom_{soil} = 1 L/kg and N = 1 and different doses: the advised dose, the highest dose calculated from the task map (61.5% reduction in applied PPP related to the advised dose) and the average of the specific minimum effective dose (65.5% reduction in applied PPP related to the advised dose).*

Case Nr.	Type dose (kg a.i./ha)	Organic matter content of top 30 cm (%)	80th percentile leaching concentration (µg/L)
2	0.85 (A: advised dose)	4.74	6.373
3	0.3273 (B: 61.5% reduction)	4.74	2.454
4	0.2933 (C: 65.5% reduction)	4.74	2.194
5	0.85 (A: advised dose)	3.6	6.603
6	0.3273 (B: 61.5% reduction)	3.6	2.542
7	0.2933 (C: 65.5% reduction)	3.6	2.276

Figure 6 shows the cumulative frequency distributions of the leaching concentrations of case 1 for substance properties sets 1 and 2. Note that a correction was done for the area that was represented. This correction was implemented via the number of dots shown in the graph. The patch with the smallest area is represented in the graph by one dot and e.g. a patch with an area 20 times as large as the smallest patch has 20 dots in the graph. For this Wing-P case one dot represents an area of 1.57 m^2. The 50th percentile in this graph represents the median of the 80th percentile leaching concentration. Note that in case the distribution of the dots is skewed, the median and the average do not coincide. In case of a positive skew, the median (50th percentile) is smaller than the average (as for set 1; see Annex 4) and in case of a negative skew the median is larger than the average (as for set 2; see Annex 4).

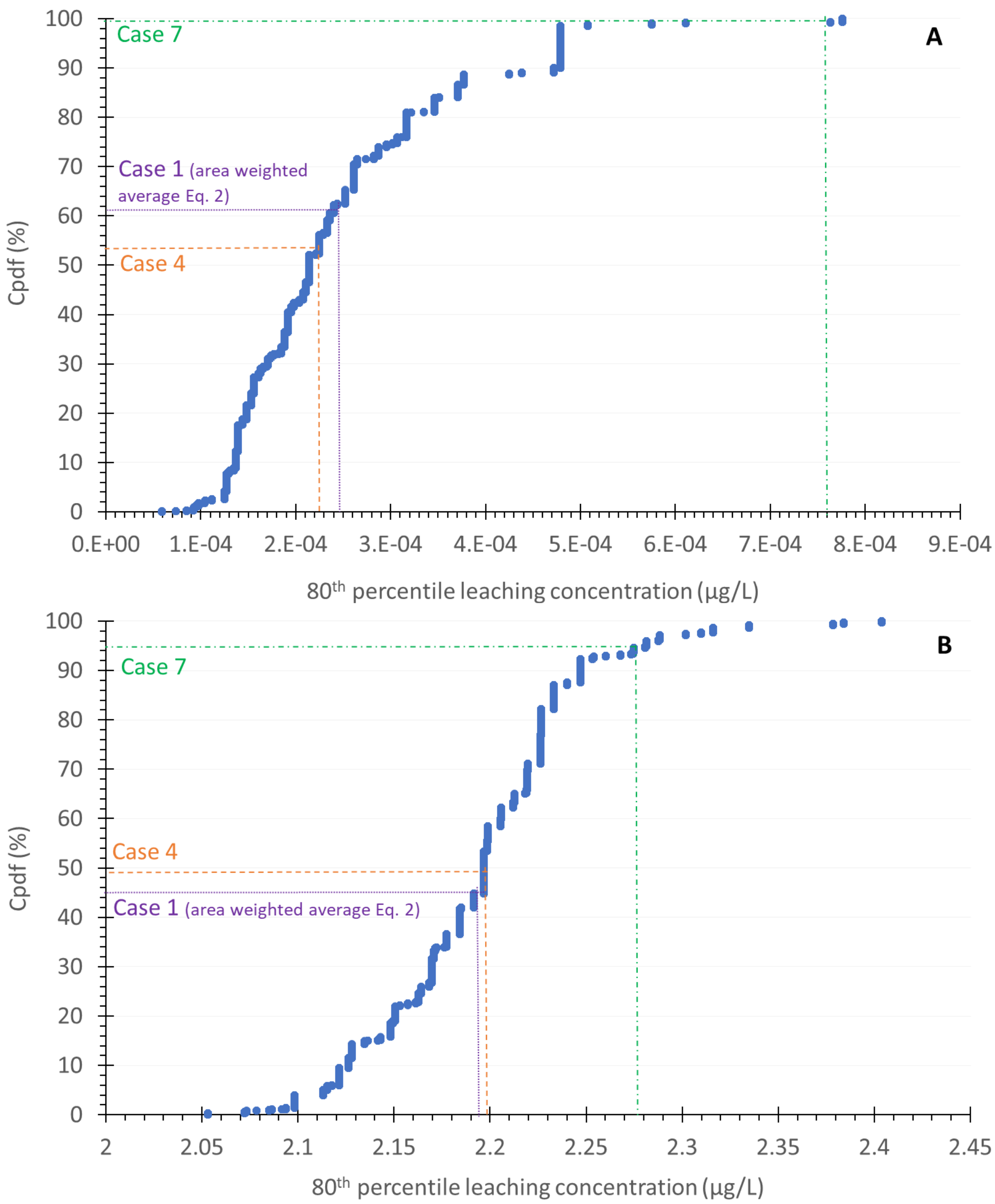

Figure 6 *Cumulative frequency distribution density plots of the 80th percentile leaching concentrations resulting from PEARL simulations for 164 plots of variable sizes using variable rate and mass organic matter content for the top 30 cm of soil (case 1) and for two sets of substance properties: set 1: actual properties of dimethenamid-P (graph A) and set 2: properties of dimethenamid-P, but with the* Kom_{soil} *set to 1 L/kg and the Freundlich exponent set to 1 (graph B). Each dot represents the 80th percentile leaching concentration of an area of 1.57* m^2*. The area weighted average (Eq. 2) is indicated via the purple dotted lines and the results of case 4 (orange dashed line) and case 7 (green dash-dot-dash line) with the Kremsmünster scenario are indicated as well.*

Figure 6A shows that for set 1 the calculated concentration of case 7 (using C: 65.5% reduction of the dose in the calculations with the Kremsmünster scenario) is almost equal to the calculated highest concentrations when simulating the 164 patches individually (case 1).

In case all patches are considered equally important, the average is a better measure than the median (i.e. 50^{th} percentile in Figure 6A). Therefore, for substance properties sets 1 and 2, the results of case 1 (Table 3) are compared to the results of cases 2, 3 and 4 (i.e. the PEARL simulations with the Kremsmünster scenario, using the area weighted average of the organic matter content of the top 30 cm of the Wing-P field: 4.74%).

For set 1, the area weighted average concentration from the simulations with variable dosing (case 1) is lower than the leaching concentrations simulated for case 2 and 3 (i.e. the Kremsmünster scenario simulations using A: the advised dose and B: 61.5% reduction). The area weighted average concentration from the simulations with variable dosing (case 1) is about a factor 1.1 higher than the simulated concentration of case 4 (i.e. the Kremsmünster scenario simulation using C: 65.5% reduction). This confirms the earlier stated hypothesis that concentrations are not averaged out over the field, for substances with non-linear sorption. Note that the non-linearity of sorption of the substance of set 1 is not very strong (Freundlich coefficient of 0.965). For substances with stronger non-linearity sorption the difference between the 80^{th} percentile leaching concentration from one simulation using an average dose and the area weighted average of the 80^{th} percentile leaching concentration of a series of PEARL simulations with variable dosing and variable organic matter content, is expected to be larger.

Next, the same comparison is made for substance properties set 2. For set 2 the same conclusion can be drawn as for set 1. The area weighted average concentration from the simulations with variable dosing (case 1) is lower than the concentrations of cases 5 and 6. The area weighted average of the 80^{th} percentile leaching concentration from the simulations with variable dosing (case 1) and the simulated concentration for case 7 (the Kremsmünster scenario simulation using C: 65.5% reduction) are similar (2.194 μg/L) as expected. The results of set 2 confirm that for substances with linear sorption one simulation using an average dose is adequate to determine the leaching to groundwater. An additional confirmation is given by calculating the reduction in leaching concentration compared to A: the advised dose. For a substance with linear sorption behaviour these reductions are expected to be the same as the reduction in applied PPP related to the advised dose. Case 7 (C: 65.5% reduction) results in 2.194 μg/L which is a reduction in concentration of 65.5% related to the concentration calculated using the advised dose (case 5 – 6.373 μg/L). Similar, case 6 results in 2.454 μg/L which is a reduction in concentration of 61.5% related to the concentration calculated for case 5.

Another interesting aspect to highlight is the effect of organic matter content for sorptive substances on the calculated leaching concentrations. Table 4 (Set 1, Kom_{soil} of 66 L/kg) shows for the same dose large differences in leaching concentrations for the different values of mass organic matter content. The leaching concentration increases as the organic matter content decreases. This is illustrated in Figure 7A for the PEARL simulations with variable dosing.

Table 5 (set 2, Kom_{soil} of 1 L/kg) shows that for the same dose, the difference in leaching concentration is very small for either using an organic matter content of 4.74% or 3.6%, which is to be expected for a substance that is (almost) not sorbing. For less sorptive substances, not the organic matter content, the dose is the most important driving factor for the leaching concentration. This is also illustrated by the relation between the leaching concentrations and organic matter content resulting from the PEARL simulations with variable dosing, showing even increasing leaching concentrations for increasing organic matter content (Figure 7B).

This is rather logical, as sorption becomes negligible, the dose becomes the driving factor for the leaching concentration. This is illustrated in Figure 8. For set 2 the leaching concentration increases as the dose increases. In contrast, for set 1 the leaching concentration decreases as the dose increases. The latter is explained by sorption to organic matter being the most important process influencing the leaching of substance to groundwater, whereas the dose is of less importance.

It should be thought, that the applied relationship between dose and organic matter content of Figure 5 and based on Eq. 1 is unrealistic for set 2 as values of all parameters in Eq. 1 (i.e. the minimum dose, maximum dose and parameters a and b) are pesticide product specific. For the 'artificial substance' of set 2 it is probably not possible to determine such a clear relationship using Eq. 1 as for the Wing-P case (Figure 5) because sorption is negligible.

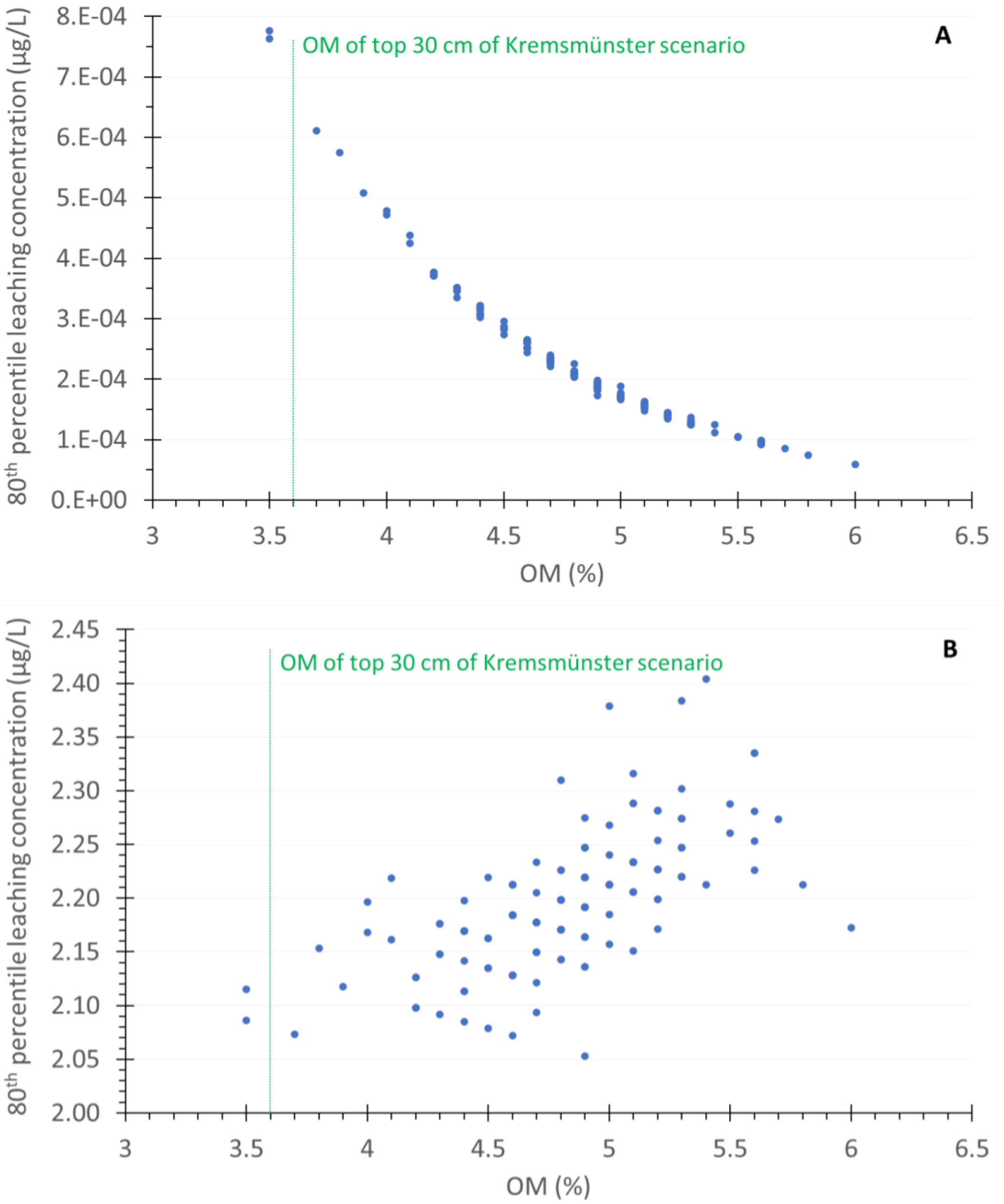

Figure 7 *The 80th percentile leaching concentrations as function of mass organic matter fraction in the top 30 cm of the soil resulting from PEARL simulations for 164 patches of variable sizes using variable rate and mass organic matter content for the top 30 cm of soil and for two sets of substance properties: 1) actual properties of dimethenamid-P (graph A) and 2) properties of dimethenamid-P, but with the Kom_{soil} set to 1 L/kg and the Freundlich exponent set to 1 (graph B). The dotted green line indicates the mass organic matter content of the top 30 cm of the FOCUS groundwater Kremsmünster scenario.*

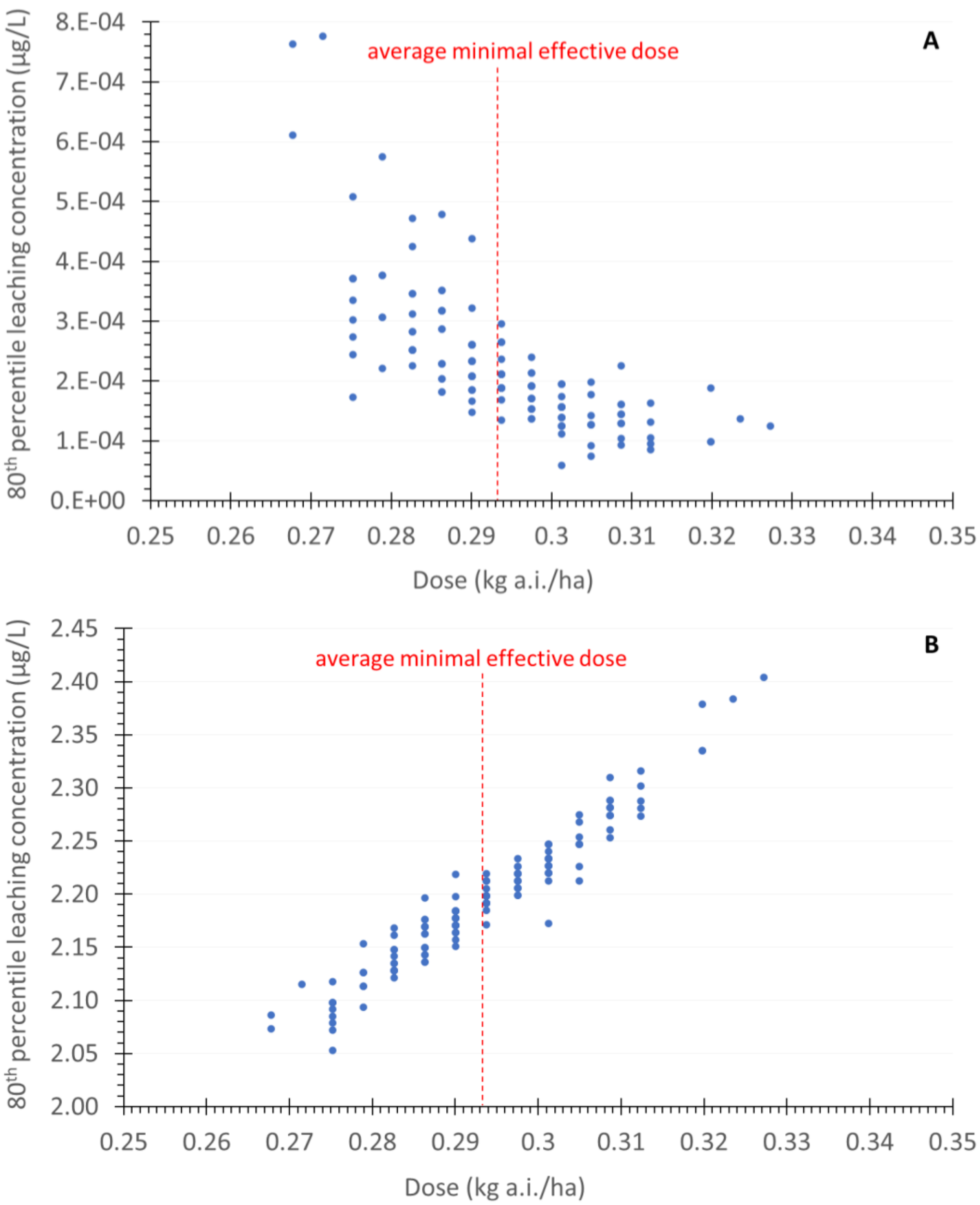

Figure 8 *The 80^{th} percentile leaching concentrations as function of dose resulting from PEARL simulations for 164 plots of variable sizes using variable rate and mass organic matter content for the top 30 cm of soil and for two sets of substance properties: 1) actual properties of dimethenamid-P (graph A) and 2) properties of dimethenamid-P, but with the Kom_{soil} set to 1 L/kg and the Freundlich exponent set to 1 (graph B). The dashed red line indicates the area weighted average of the specific minimum effective dose (i.e. C: 65.5% reduction in applied PPP related to the advised dose).*

Note, that we did not quantify the tipping point of the sorption coefficient at which the leaching concentration is not increasing with organic matter content but also not increasing with the dose (which is correlated to the mass organic matter content). In theory, it might be an interesting exercise, to indicate for which combinations of Kom_{soil} and parameter a and b in Eq. 1 the calculated leaching concentration is dose dominated and for which it is sorption dominated. In practice this is rather difficult as the decision-making model for variable rate applications (e.g. values of minimum dose, maximum dose and parameters a and b in Eq. 1) is unique for each situation (a combination of PPP, field and the circumstances around the timing of application).

Another interesting aspect to study is the effect of non-linearity of sorption. We did consider this and performed a few PEARL simulations using the default Freundlich coefficient of 0.9 (and thus assuming more non-linearity in sorption than in substance properties set 1). However, these test simulations all resulted in very low leaching concentrations for our case study, which led to the decision not to investigate this any further. In Annex 5 it is explained why a lower Freundlich coefficient leads to lower leaching concentrations.

4 Conclusions

The aim of the modelling exercise described was to test the hypothesis that for substances with non-linear sorption risks are not averaged out over the field and that it might consequently not be justified to regard the total reduced pesticide use as result of variable rate applications as a mitigation measure in the leaching assessment for pesticide registration purposes.

This was tested by comparing the leaching concentrations as result of two simulations with reduced pesticide doses (61.5% and 65.5% reduction in applied PPP related to the advised dose) with the area weighted average leaching concentration of a series of simulations for all situations in the field with variable rate applications.

For the particular case that was studied (*PPP* Wing-P application; active ingredient dimethenamid-P; Kom_{soil} of 66.12 L/kg) the variable dosing was based on the organic matter content per patch in the field, i.e. a higher organic matter content results in a higher dose. Simulations showed that applying the area averaged (reduced) dose as result of variable rate applications results in a different leaching concentration than using the average of a series of different dose applications applied per patch in the field. The difference is, however small due to the rather weak non-linearity of sorption of dimethenamid-P (Freundlich coefficient of 0.965). This indicates that in the groundwater leaching assessment for PPPs, the area averaged (reduced) dose could be used for substances with weak non-linear sorption. Substances with stronger non-linearity of sorption might show larger differences between the two types of concentrations. For these substances averaging of the dose may not be justified.

It was furthermore shown that for this specific case, sorption to organic matter was the most important process influencing the leaching of substance to groundwater. Despite the higher dosing in patches with higher organic matter in the top soil, the leaching concentration decreased with increasing organic matter content. Simulations with a less sorptive substance (Kom_{soil} = 1 L/kg), for the same variation in dosing the dose became more important than the sorption.

The Kremsmünster scenario as used for leaching assessments for pesticide registration purposes was shown to be protective for 99% of patches in the field of the case study. This is due to the fact that the organic matter content in the top 30 cm soil of the actual field of the Wing-P case is for most patches in the field higher than the organic matter content of the top 30 cm of the FOCUS groundwater Kremsmünster scenario. The Kremsmünster scenario is assumed to be protective for 90% of all situations in the Netherlands. This scenario is probably not protective for cases where the organic matter content of the actual field is lower than the organic matter content of the top 30 cm of the Kremsmünster scenario. It would be interesting to assess for which fields in the Netherlands this would apply.

5 Outlook for leaching assessments

For the groundwater leaching assessment as part of the pesticide registration procedure it is of interest whether predefined reduction in the dosing could be adopted as a mitigation measure. As concluded from this study, this approach is defensible for substances with linear sorption or weak non-linearity of sorption. To do so, for these substances simulations could be done with e.g. the Kremsmünster scenario and the predefined reduced dose.

How to establish such a predefined reduced dose is a topic of discussion. In principle, a reduced dose is case specific, i.e. specific for the use a particular PPP in one particular field and the local conditions around the time of application of this PPP. Using the reduced dose of one specific case in the leaching assessment does not necessarily lead to a leaching endpoint that is protective for all other fields (spatial component) and their local conditions around the time of application (temporal component).

To find a reduced dose (e.g. the average of the minimum effective dose or the highest dose calculated from the task map or the as-applied map) for a particular PPP that is for instance protecting 90% of all possible situations (in time and space) a probabilistic approach could be used. Therefore, it would be needed to determine a large series of dose-soil scan parameter relationships (one relationship per case). The resulting series of the reduced dose could be used to make a cumulative density plot and subsequently from this plot the dose that is larger than e.g. 90% of all doses calculated can be selected. This idea is illustrated in Figure 9.

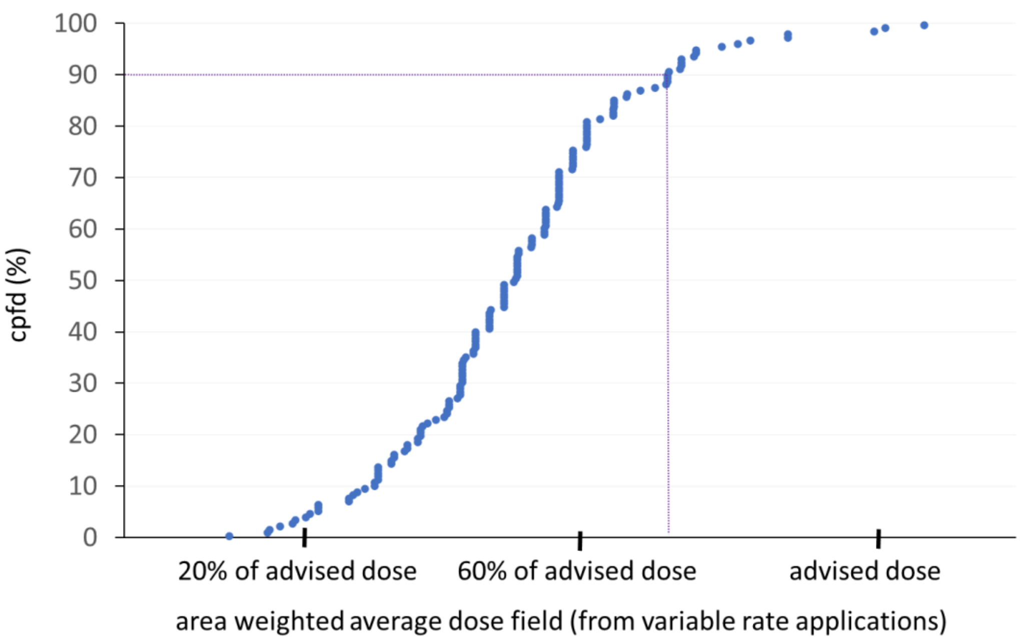

Figure 9 *Illustration of a fictional cumulative probability frequency distribution (cpfd) of reduced doses a result of variable rate applications. Each dot represent a reduced dose determined from a dose-soil scan parameter relation (Eq.1) that is unique for a certain field and the local circumstances around the time of application for which the dose-soil scan parameter relation was developed.*

The main obstacle for establishing a predefined reduced dose is currently the limited availability of dose-soil scan parameter relations. Reductions in applied PPP (related to the advised dose) calculated according decision-making models for variable rate applications based on soil scan parameters (organic matter content, OM – Eq.1) might vary between fields, as there is considerable variety in soil scan parameters within the

Netherlands. Moreover, each situation (a field and the circumstances around the timing of application) has its own unique decision-making model for variable rate applications (e.g. unique values of minimum dose, maximum dose and parameters a and b in Eq. 1).

Next to the obstacle for developing the probabilistic approach as explained above (i.e. limited availability of dose-soil scan parameter relations) detailed information on soil organic matter content in the Netherlands at a very high spatial resolution is needed.

Concluding, using a reduced dose for a particular PPP as result of precision application techniques in the leaching assessment for regulatory purposes is defensible for substances with linear sorption or weak non-linearity of sorption. However, this reduced dose must be based on a study on multiple cases in the area of use (i.e. the Netherlands). Each case has its own specific conditions (both spatially and temporally) that determine the achieved reduction in the dosing. Using the reduced dose of one specific case in the leaching assessment does not necessarily lead to a leaching endpoint that is protective for all other possible situations.

References

Adriaanse, P.I., Buddendorf, W.B., Holterman, H.J., & ter Horst, M.M.S. 2022. Supporting the development of exposure assessment scenarios for Non-Target Terrestrial Organisms to plant protection products: Development of Exposure Assessment Goals. EFSA Supporting Publications, 19(11), Article 7661E. https://doi.org/10.2903/sp.efsa.2022.EN-7661.

Boesten, J.J.T.I. and A.M.A. van der Linden. 1991. Modeling the influence of sorption and transformation on pesticide leaching and persistence. Journal of Environmental Quality 20: 425-435. https://doi.org/10.2134/jeq1991.00472425002000020015x.

Boheemen, K. van, Riepma, J. & Huijsmans, J.F.M., 2022. Precision Agriculture and Crop Protection; Definitions and the relation between precision-applications and the authorisation procedure of PPPs. Wageningen Research, Report WPR-1118. https://doi.org/10.18174/566499.

Ctgb, 2021. Authorised products database. Website: https://pesticidesdatabase.ctgb.nl/en/authorisations (last entered 24 December 2021).

European and Mediterranean Plant Protection Organization. 2012. PP 1/225(2) Minimum effective dose. Bulletin OEPP/EPPO Bulletin (2012)42(3), 403-404. ISSN 0250-8052. doi: 10.1111/epp.21612.

Kempenaar, C., Heijting, S., Kessel, G.J.T., Michielsen, J.G.P., Wijnholds, K.H. 2013. Modellen en beslisregels voor variabel doseren van gewasbeschermingsmiddelen op basis van variatie in bodem en gewas. Rapportage PPL-project 80. PRI-WUR Rapport 496b. https://edepot.wur.nl/291354.

EFSA, 2005. Scientific Report (2005) 53, 1-73, Conclusion on the peer review of dimethenamid. doi: 10.2903/j.efsa.2006.53r.

FOCUS. 2000. FOCUS groundwater scenarios in the EU review of active substances. EC Document Reference SANCO/321/2000 rev2.

Ministry of Agriculture, Nature and Food Quality. 2023. Implementation programme for the Vision for the Future of Plant Protection 2030. Website: https://www.government.nl/documents/publications/2023/01/27/implementation-programme-for-the-vision-for-the-future-of-plant-protection-2030 (last entered 16 February 2023).

Heinen, M., Bakker, G., & Wösten, J.H.M. 2020. Waterretentie- en doorlatendheidskarakteristieken van boven- en ondergronden in Nederland: de Staringreeks: Update 2018. (Wageningen Environmental Research rapport; No. 2978). Wageningen Environmental Research. https://doi.org/10.18174/512761.

Van den Berg, F., Tiktak, A., Boesten, J.J.T.I., Van der Linden A.M.A. 2016. PEARL model for pesticide behaviour and emissions in soil-plant systems; Description of processes. The Statutory Research Tasks Unit for Nature & the Environment (WOT Natuur & Milieu). WOt-technical report 61. https://edepot.wur.nl/377664.

Van der Linden, A.M.A., Boesten, J.J.T.I., Cornelese, A.A., Kruijne, R., Leistra, M., Linders, J.B.H.J., Pol, J.W., Tiktak, A., Verschoor, A.J. 2004. The new decision tree for the evaluation of pesticide leaching from soils. RIVM report 601450019, RIVM, Bilthoven, 57 p. https://www.rivm.nl/bibliotheek/rapporten/601450019.pdf.

Annex 1 Data for the Wing-P case

Table 6 specifies for each patch of the treated field the spraying volume applied, the dose of product Wing-P applied, the dose of active ingredient dimethenamid-P, the area and the average soil organic matter content of the top 30 cm soil. Spraying volume, soil organic matter content and area of the patch were provided by Koen van Boheemen of Wageningen Plant Research. Based on the information that 400 L/ha of spraying volume equals 1.4 L Wing-P/ha, for each patch the dose of Wing-P was calculated. The dose of active ingredient dimethenamid-P for each patch is calculated based on the information that the content of dimethenamid-P in Wing-P is 212.5 g a.i./L Wing-P (Ctgb authorized products database, visited on 16 September 2021). Note that for the simulation with variable dosing, the data i.e. the dose in kg active ingredient/ha and the mass fraction of organic matter content were written to the input file of PEARL in real numbers in digital form with six digital places.

Table 6 *Specifying in for each patch of the treated field of the case study the spraying volume applied, the dose of product Wing-P applied, the dose of active ingredient dimethenamid-P, the area and the average soil organic matter content of the top 30 cm soil.*

Patch ID	Spraying volume (L/ha)	Average soil organic matter content of the top 30 cm (%)	Area of the patch (m2)	Dose WingP (L/ha)	Dose (kg a.i./ha)
1	360	3.7	180.49	1.2600	0.2678
2	360	3.5	24.40	1.2600	0.2678
3	365	3.5	617.05	1.2775	0.2715
4	370	4.5	16.65	1.2950	0.2752
5	370	3.9	173.24	1.2950	0.2752
6	370	4.6	240.49	1.2950	0.2752
7	370	4.3	73.07	1.2950	0.2752
8	370	4.2	1664.58	1.2950	0.2752
9	370	4.2	240.48	1.2950	0.2752
10	370	4.9	240.54	1.2950	0.2752
11	370	4.4	187.56	1.2950	0.2752
12	370	4.2	156.25	1.2950	0.2752
13	375	4.4	35.62	1.3125	0.2789
14	375	4.4	915.97	1.3125	0.2789
15	375	4.2	1201.33	1.3125	0.2789
16	375	4.2	511.18	1.3125	0.2789
17	375	3.8	220.84	1.3125	0.2789
18	375	4.7	240.49	1.3125	0.2789
19	380	4.6	50.81	1.3300	0.2826
20	380	4.3	2171.94	1.3300	0.2826
21	380	4.4	91.51	1.3300	0.2826
22	380	4.6	627.17	1.3300	0.2826
23	380	4.6	424.91	1.3300	0.2826
24	380	4.5	320.04	1.3300	0.2826
25	380	4.3	185.09	1.3300	0.2826
26	380	4.1	199.52	1.3300	0.2826
27	380	4.7	2881.47	1.3300	0.2826
28	380	4.6	240.37	1.3300	0.2826
29	380	4.6	961.22	1.3300	0.2826
30	380	4.5	240.42	1.3300	0.2826
31	380	4	721.29	1.3300	0.2826
32	385	4.3	109.84	1.3475	0.2863

Patch ID	Spraying volume (L/ha)	Average soil organic matter content of the top 30 cm (%)	Area of the patch (m2)	Dose WingP (L/ha)	Dose (kg a.i./ha)
33	385	4.7	54.49	1.3475	0.2863
34	385	4.9	58.77	1.3475	0.2863
35	385	4.9	42.85	1.3475	0.2863
36	385	4.8	240.42	1.3475	0.2863
37	385	4.4	164.22	1.3475	0.2863
38	385	4.5	63.52	1.3475	0.2863
39	385	4.3	19.40	1.3475	0.2863
40	385	4.4	76.98	1.3475	0.2863
41	385	4.7	120.19	1.3475	0.2863
42	385	4.8	240.54	1.3475	0.2863
43	385	4.4	1681.81	1.3475	0.2863
44	385	4	7146.15	1.3475	0.2863
45	385	4.4	2162.17	1.3475	0.2863
46	385	4.7	240.42	1.3475	0.2863
47	385	4.5	1424.45	1.3475	0.2863
48	390	5	307.17	1.3650	0.2901
49	390	4.4	91.81	1.3650	0.2901
50	390	4.7	374.56	1.3650	0.2901
51	390	4.9	480.80	1.3650	0.2901
52	390	4.9	240.49	1.3650	0.2901
53	390	4.8	240.49	1.3650	0.2901
54	390	4.6	1201.21	1.3650	0.2901
55	390	4.8	240.54	1.3650	0.2901
56	390	4.8	240.49	1.3650	0.2901
57	390	4.7	230.85	1.3650	0.2901
58	390	4.6	1681.40	1.3650	0.2901
59	390	4.7	12.12	1.3650	0.2901
60	390	4.8	26.53	1.3650	0.2901
61	390	4.8	84.14	1.3650	0.2901
62	390	4.7	218.52	1.3650	0.2901
63	390	4.6	127.46	1.3650	0.2901
64	390	4.9	333.19	1.3650	0.2901
65	390	4.7	78.70	1.3650	0.2901
66	390	4.6	94.89	1.3650	0.2901
67	390	4.1	206.57	1.3650	0.2901
68	390	4.7	1201.61	1.3650	0.2901
69	390	5.1	2401.96	1.3650	0.2901
70	390	4.6	480.89	1.3650	0.2901
71	390	4.8	240.38	1.3650	0.2901
72	390	4.8	240.36	1.3650	0.2901
73	390	4.6	720.84	1.3650	0.2901
74	395	4.8	240.54	1.3825	0.2938
75	395	4.9	480.77	1.3825	0.2938
76	395	4.9	240.42	1.3825	0.2938
77	395	4.8	240.54	1.3825	0.2938
78	395	4.8	240.42	1.3825	0.2938
79	395	5.2	479.98	1.3825	0.2938
80	395	4.8	135.89	1.3825	0.2938
81	395	4.9	480.54	1.3825	0.2938
82	395	4.9	480.53	1.3825	0.2938
83	395	4.6	178.19	1.3825	0.2938
84	395	4.8	64.38	1.3825	0.2938
85	395	4.9	240.48	1.3825	0.2938
86	395	4.8	475.89	1.3825	0.2938

Patch ID	Spraying volume (L/ha)	Average soil organic matter content of the top 30 cm (%)	Area of the patch (m2)	Dose WingP (L/ha)	Dose (kg a.i./ha)
87	395	4.9	79.74	1.3825	0.2938
88	395	4.6	240.49	1.3825	0.2938
89	395	4.9	69.79	1.3825	0.2938
90	395	4.9	240.42	1.3825	0.2938
91	395	5	240.49	1.3825	0.2938
92	395	4.8	240.48	1.3825	0.2938
93	395	4.5	480.66	1.3825	0.2938
94	395	4.7	1199.10	1.3825	0.2938
95	395	4.6	480.84	1.3825	0.2938
96	400	5	142.33	1.4000	0.2975
97	400	4.8	105.80	1.4000	0.2975
98	400	5.1	31.83	1.4000	0.2975
99	400	4.9	90.34	1.4000	0.2975
100	400	5.2	358.11	1.4000	0.2975
101	400	5	190.96	1.4000	0.2975
102	400	5.1	207.78	1.4000	0.2975
103	400	5	240.36	1.4000	0.2975
104	400	4.9	240.36	1.4000	0.2975
105	400	4.9	365.79	1.4000	0.2975
106	400	5.2	2169.16	1.4000	0.2975
107	400	4.9	681.62	1.4000	0.2975
108	400	4.9	1441.27	1.4000	0.2975
109	400	4.7	1355.71	1.4000	0.2975
110	400	5	480.44	1.4000	0.2975
111	400	4.8	4513.49	1.4000	0.2975
112	400	4.9	480.77	1.4000	0.2975
113	400	5.1	1720.49	1.4000	0.2975
114	405	5.1	125.71	1.4175	0.3012
115	405	6	73.40	1.4175	0.3012
116	405	5.2	240.38	1.4175	0.3012
117	405	5.1	11.06	1.4175	0.3012
118	405	5.3	193.06	1.4175	0.3012
119	405	5.3	157.04	1.4175	0.3012
120	405	5	409.51	1.4175	0.3012
121	405	5.2	52.60	1.4175	0.3012
122	405	5.3	266.52	1.4175	0.3012
123	405	4.9	445.98	1.4175	0.3012
124	405	4.9	480.54	1.4175	0.3012
125	405	4.9	38.18	1.4175	0.3012
126	405	5.1	15.18	1.4175	0.3012
127	405	5.1	128.00	1.4175	0.3012
128	405	5.1	240.38	1.4175	0.3012
129	405	5.1	62.54	1.4175	0.3012
130	405	5.3	480.37	1.4175	0.3012
131	405	5.2	1682.16	1.4175	0.3012
132	405	5.2	2378.74	1.4175	0.3012
133	405	5.1	1921.15	1.4175	0.3012
134	405	5.1	240.54	1.4175	0.3012
135	405	5.4	240.54	1.4175	0.3012
136	410	5.8	71.32	1.4350	0.3049
137	410	5.6	257.28	1.4350	0.3049
138	410	5.3	3.36	1.4350	0.3049
139	410	5	207.09	1.4350	0.3049
140	410	5.3	1201.01	1.4350	0.3049

Patch ID	Spraying volume (L/ha)	Average soil organic matter content of the top 30 cm (%)	Area of the patch (m2)	Dose WingP (L/ha)	Dose (kg a.i./ha)
141	410	5.2	175.03	1.4350	0.3049
142	410	4.9	686.18	1.4350	0.3049
143	410	5.3	1770.74	1.4350	0.3049
144	415	5.3	240.38	1.4525	0.3087
145	415	5.2	81.67	1.4525	0.3087
146	415	5.1	240.48	1.4525	0.3087
147	415	5.5	184.95	1.4525	0.3087
148	415	5.1	480.49	1.4525	0.3087
149	415	5.3	69.82	1.4525	0.3087
150	415	5.3	12.10	1.4525	0.3087
151	415	5.6	240.54	1.4525	0.3087
152	415	5.2	1.57	1.4525	0.3087
153	415	4.8	240.49	1.4525	0.3087
154	415	5.2	775.89	1.4525	0.3087
155	420	5.7	98.76	1.4700	0.3124
156	420	5.5	240.49	1.4700	0.3124
157	420	5.6	284.32	1.4700	0.3124
158	420	5.1	780.31	1.4700	0.3124
159	420	5.3	223.11	1.4700	0.3124
160	430	5	240.49	1.5050	0.3198
161	430	5.6	17.73	1.5050	0.3198
162	430	5.6	437.96	1.5050	0.3198
163	435	5.3	240.49	1.5225	0.3235
164	440	5.4	226.34	1.5400	0.3273

Annex 2 Substance properties of active substances pendimethalin and dimethenamid-P in PPP Wing-P

Table 7 *Substance properties of pendimethalin and dimethenamid-P taken from resp. EFSA, 2016 and EFSA, 2005.*

	pendimethalin (herbicide, dinitroaniline; systemic)	**dimethenamid-P (herbicide, chloroacetamide; non-systemic)**
M_{mol} g/mol	281.3	275.79
P_{sat} Pa	3.0 E-4	3.7 10^{-2} Pa
T P_{sat} C	20	25
C_{sol} mg/L	0.33	1400
T C_{sol} C	20	20
Kom_{soil} L/kg	8000	66.12
Freundl. exp.	0.954	0.965
$DegT50_{soil}$ d	182.28	13

Parameters that were assumed to be substance independent

- E_a for degradation in soil: 65.4 kJ/mol (EFSA, 2007).
- Factor *B* describing moisture dependency of degradation in soil: 0.7 (FOCUS 2000).
- Wash-off factor: 100 m^{-1} conservative value based on EFSA (2017).
- Depth dependency of degradation in soil as proposed by FOCUS (2000)[7].
- Uptake factor for plants: 0.5 for systemic substance and 0.0 for non-systemic substances[8] (FOCUS 2000).
- Molar enthalpy of vaporisation: 95 kJ/mol (FOCUS 2000).
- Molar enthalpy of dissolution: 27 kJ/mol (FOCUS 2000).
- Molar enthalpy of sorption: 0 kJ/mol (FOCUS 2000).
- Reference diffusion coefficient in water: 0.43 10^{-4} m^2 d^{-1} (FOCUS 2000).
- Reference diffusion coefficient in air: 0.43 m^2 d^{-1} (FOCUS 2000).
- Reference temperatures for diffusion, vapour pressure, water solubility, sorption, transformation rates in soil and water: 20 °C.
- Reference moisture content for degradation: pF 2.
- Half-life for degradation on plant surfaces: 10 d. EFSA (2017).

[7] i.e. in the PEARL *.prl file the following is done

```
table interpolate
FacZTra    (-)              Factor for the effect of depth [0|1]
hor Ip
0.01   1
0.29   1
0.2    0.5
0.1   0.5
0.4   0.3
0.5   0
3     0
end_table
```

[8] In case the substance is non-systemic, FOCUS (2000) recommends an uptake factor of 0.0. For systemic substances an uptake factor of 0.5 is recommended.

Table 8 *Information on the mode of action of pendimethalin and dimethenamid-P.*

	pendimethalin (herbicide, dinitroaniline; systemic)	dimethenamid-P (herbicide, chloroacetamide; non-systemic)
Mode of action	Inhibitor of plant cell division and cell elongation that interferes with the germination process and seedling development.	Protein synthesis inhibitor that is used for control of germinating seeds and very small emerged seedlings of many annual grasses and few small seeded broadleaf species.

References

EFSA (European Food Safety Authority). 2007. Opinion on a request from EFSA related to the default Q10 value used to describe the temperature effect on transformation rates of pesticides in soil. Scientific Opinion of the Panel on Plant Protection Products and their Residues (PPR-Panel). EFSA Journal 622: 1-32. doi: 10.2903/j.efsa.2008.622.

EFSA (European Food Safety Authority). 2017. EFSA Guidance Document for predicting environmental concentrations of active substances of plant protection products and transformation products of these active substances in soil. EFSA Journal 2017;15(10):4982, 115 pp. https://doi.org/10.2903/j.efsa.2017.4982.

EFSA (European Food Safety Authority). 2016. Peer review of the pesticide risk assessment of the active substance pendimethalin. doi: 10.2903/j.efsa.2016.4420.

EFSA (European Food Safety Authority). 2005. Scientific Report (2005) 53, 1-73, Conclusion on the peer review of dimethenamid. doi: 10.2903/j.efsa.2006.53r.

FOCUS. 2000. FOCUS groundwater scenarios in the EU review of active substances. EC Document Reference SANCO/321/2000 rev2.

Annex 3 Results of simulations sets 1 and 2

Table 9 *Specifying in for each patch of the treated field of the case study the dose of active ingredient dimethenamid-P, the average soil organic matter content of the top 30 cm soil, the area of the patch and the simulated 80th percentile leaching concentrations for simulations Substance properties Sets 1 and 2.*

Grid ID	Dose (kg a.i./ ha)	Mass organic matter fraction (-)	Area of the patch (m^2)	80th percentile leaching concentration (ug/L)	
				set 1: substance properties according Annex 2	set 2: KOM = 1 L/kg and N = 1
1	0.26775	0.037	180.49	0.000611	2.073402
2	0.26775	0.035	24.40	0.000763	2.086392
3	0.271469	0.035	617.05	0.000776	2.115372
4	0.275188	0.045	16.65	0.000274	2.078584
5	0.275188	0.039	173.24	0.000508	2.117742
6	0.275188	0.046	240.49	0.000244	2.072148
7	0.275188	0.043	73.07	0.000335	2.091538
8	0.275188	0.042	1664.58	0.000371	2.098052
9	0.275188	0.042	240.48	0.000371	2.098052
10	0.275188	0.049	240.54	0.000173	2.052974
11	0.275188	0.044	187.56	0.000302	2.085048
12	0.275188	0.042	156.25	0.000371	2.098052
13	0.278906	0.044	35.62	0.000307	2.113226
14	0.278906	0.044	915.97	0.000307	2.113226
15	0.278906	0.042	1201.33	0.000377	2.126406
16	0.278906	0.042	511.18	0.000377	2.126406
17	0.278906	0.038	220.84	0.000575	2.153064
18	0.278906	0.047	240.49	0.000221	2.093649
19	0.282625	0.046	50.81	0.000252	2.128156
20	0.282625	0.043	2171.94	0.000346	2.14807
21	0.282625	0.044	91.51	0.000312	2.141405
22	0.282625	0.046	627.17	0.000252	2.128156
23	0.282625	0.046	424.91	0.000252	2.128156
24	0.282625	0.045	320.04	0.000282	2.134766
25	0.282625	0.043	185.09	0.000346	2.14807
26	0.282625	0.041	199.52	0.000425	2.161476
27	0.282625	0.047	2881.47	0.000225	2.121567
28	0.282625	0.046	240.37	0.000252	2.128156
29	0.282625	0.046	961.22	0.000252	2.128156
30	0.282625	0.045	240.42	0.000282	2.134766
31	0.282625	0.04	721.29	0.000472	2.168216
32	0.286344	0.043	109.84	0.000351	2.176336
33	0.286344	0.047	54.49	0.000229	2.149484
34	0.286344	0.049	58.77	0.000182	2.136209
35	0.286344	0.049	42.85	0.000182	2.136209
36	0.286344	0.048	240.42	0.000204	2.142833
37	0.286344	0.044	164.22	0.000317	2.169583
38	0.286344	0.045	63.52	0.000287	2.162857
39	0.286344	0.043	19.40	0.000351	2.176336
40	0.286344	0.044	76.98	0.000317	2.169583
41	0.286344	0.047	120.19	0.000229	2.149484
42	0.286344	0.048	240.54	0.000204	2.142833
43	0.286344	0.044	1681.81	0.000317	2.169583

Grid ID	Dose (kg a.i./ ha)	Mass organic matter fraction (-)	Area of the patch (m^2)	80th percentile leaching concentration (ug/L)	
				set 1: substance properties according Annex 2	set 2: KOM = 1 L/kg and N = 1
44	0.286344	0.04	7146.15	0.000479	2.196748
45	0.286344	0.044	2162.17	0.000317	2.169583
46	0.286344	0.047	240.42	0.000229	2.149484
47	0.286344	0.045	1424.45	0.000287	2.162857
48	0.290063	0.05	307.17	0.000166	2.157269
49	0.290063	0.044	91.81	0.000322	2.197761
50	0.290063	0.047	374.56	0.000233	2.177401
51	0.290063	0.049	480.80	0.000185	2.163954
52	0.290063	0.049	240.49	0.000185	2.163954
53	0.290063	0.048	240.49	0.000208	2.170664
54	0.290063	0.046	1201.21	0.000261	2.184164
55	0.290063	0.048	240.54	0.000208	2.170664
56	0.290063	0.048	240.49	0.000208	2.170664
57	0.290063	0.047	230.85	0.000233	2.177401
58	0.290063	0.046	1681.40	0.000261	2.184164
59	0.290063	0.047	12.12	0.000233	2.177401
60	0.290063	0.048	26.53	0.000208	2.170664
61	0.290063	0.048	84.14	0.000208	2.170664
62	0.290063	0.047	218.52	0.000233	2.177401
63	0.290063	0.046	127.46	0.000261	2.184164
64	0.290063	0.049	333.19	0.000185	2.163954
65	0.290063	0.047	78.70	0.000233	2.177401
66	0.290063	0.046	94.89	0.000261	2.184164
67	0.290063	0.041	206.57	0.000438	2.218361
68	0.290063	0.047	1201.61	0.000233	2.177401
69	0.290063	0.051	2401.96	0.000148	2.15061
70	0.290063	0.046	480.89	0.000261	2.184164
71	0.290063	0.048	240.38	0.000208	2.170664
72	0.290063	0.048	240.36	0.000208	2.170664
73	0.290063	0.046	720.84	0.000261	2.184164
74	0.293781	0.048	240.54	0.000211	2.198488
75	0.293781	0.049	480.77	0.000188	2.191691
76	0.293781	0.049	240.42	0.000188	2.191691
77	0.293781	0.048	240.54	0.000211	2.198488
78	0.293781	0.048	240.42	0.000211	2.198488
79	0.293781	0.052	479.98	0.000135	2.171457
80	0.293781	0.048	135.89	0.000211	2.198488
81	0.293781	0.049	480.54	0.000188	2.191691
82	0.293781	0.049	480.53	0.000188	2.191691
83	0.293781	0.046	178.19	0.000265	2.21216
84	0.293781	0.048	64.38	0.000211	2.198488
85	0.293781	0.049	240.48	0.000188	2.191691
86	0.293781	0.048	475.89	0.000211	2.198488
87	0.293781	0.049	79.74	0.000188	2.191691
88	0.293781	0.046	240.49	0.000265	2.21216
89	0.293781	0.049	69.79	0.000188	2.191691
90	0.293781	0.049	240.42	0.000188	2.191691
91	0.293781	0.05	240.49	0.000169	2.18492
92	0.293781	0.048	240.48	0.000211	2.198488
93	0.293781	0.045	480.66	0.000296	2.219031
94	0.293781	0.047	1199.10	0.000236	2.205311
95	0.293781	0.046	480.84	0.000265	2.21216
96	0.2975	0.05	142.33	0.000171	2.212579

Grid ID	Dose (kg a.i./ ha)	Mass organic matter fraction (-)	Area of the patch (m^2)	80th percentile leaching concentration (ug/L)	
				set 1: substance properties according Annex 2	set 2: KOM = 1 L/kg and N = 1
97	0.2975	0.048	105.80	0.000214	2.226319
98	0.2975	0.051	31.83	0.000153	2.20575
99	0.2975	0.049	90.34	0.000192	2.219436
100	0.2975	0.052	358.11	0.000137	2.198946
101	0.2975	0.05	190.96	0.000171	2.212579
102	0.2975	0.051	207.78	0.000153	2.20575
103	0.2975	0.05	240.36	0.000171	2.212579
104	0.2975	0.049	240.36	0.000192	2.219436
105	0.2975	0.049	365.79	0.000192	2.219436
106	0.2975	0.052	2169.16	0.000137	2.198946
107	0.2975	0.049	681.62	0.000192	2.219436
108	0.2975	0.049	1441.27	0.000192	2.219436
109	0.2975	0.047	1355.71	0.00024	2.233228
110	0.2975	0.05	480.44	0.000171	2.212579
111	0.2975	0.048	4513.49	0.000214	2.226319
112	0.2975	0.049	480.77	0.000192	2.219436
113	0.2975	0.051	1720.49	0.000153	2.20575
114	0.301219	0.051	125.71	0.000156	2.233324
115	0.301219	0.06	73.40	5.90E-05	2.172233
116	0.301219	0.052	240.38	0.000139	2.226435
117	0.301219	0.051	11.06	0.000156	2.233324
118	0.301219	0.053	193.06	0.000125	2.219569
119	0.301219	0.053	157.04	0.000125	2.219569
120	0.301219	0.05	409.51	0.000174	2.240239
121	0.301219	0.052	52.60	0.000139	2.226435
122	0.301219	0.053	266.52	0.000125	2.219569
123	0.301219	0.049	445.98	0.000195	2.247181
124	0.301219	0.049	480.54	0.000195	2.247181
125	0.301219	0.049	38.18	0.000195	2.247181
126	0.301219	0.051	15.18	0.000156	2.233324
127	0.301219	0.051	128.00	0.000156	2.233324
128	0.301219	0.051	240.38	0.000156	2.233324
129	0.301219	0.051	62.54	0.000156	2.233324
130	0.301219	0.053	480.37	0.000125	2.219569
131	0.301219	0.052	1682.16	0.000139	2.226435
132	0.301219	0.052	2378.74	0.000139	2.226435
133	0.301219	0.051	1921.15	0.000156	2.233324
134	0.301219	0.051	240.54	0.000156	2.233324
135	0.301219	0.054	240.54	0.000112	2.212729
136	0.304938	0.058	71.32	7.40E-05	2.212607
137	0.304938	0.056	257.28	9.20E-05	2.226271
138	0.304938	0.053	3.36	0.000127	2.246965
139	0.304938	0.05	207.09	0.000177	2.26789
140	0.304938	0.053	1201.01	0.000127	2.246965
141	0.304938	0.052	175.03	0.000142	2.253916
142	0.304938	0.049	686.18	0.000198	2.274918
143	0.304938	0.053	1770.74	0.000127	2.246965
144	0.308656	0.053	240.38	0.000129	2.274369
145	0.308656	0.052	81.67	0.000144	2.281405
146	0.308656	0.051	240.48	0.000161	2.288464
147	0.308656	0.055	184.95	0.000104	2.260378
148	0.308656	0.051	480.49	0.000161	2.288464
149	0.308656	0.053	69.82	0.000129	2.274369

Grid ID	Dose (kg a.i./ ha)	Mass organic matter fraction (-)	Area of the patch (m^2)	80th percentile leaching concentration (ug/L)	
				set 1: substance properties according Annex 2	set 2: KOM = 1 L/kg and N = 1
150	0.308656	0.053	12.10	0.000129	2.274369
151	0.308656	0.056	240.54	9.30E-05	2.253423
152	0.308656	0.052	1.57	0.000144	2.281405
153	0.308656	0.048	240.49	0.000225	2.309804
154	0.308656	0.052	775.89	0.000144	2.281405
155	0.312375	0.057	98.76	8.50E-05	2.273563
156	0.312375	0.055	240.49	0.000105	2.287613
157	0.312375	0.056	284.32	9.50E-05	2.280574
158	0.312375	0.051	780.31	0.000163	2.316038
159	0.312375	0.053	223.11	0.000131	2.301773
160	0.319813	0.05	240.49	0.000188	2.378519
161	0.319813	0.056	17.73	9.80E-05	2.33487
162	0.319813	0.056	437.96	9.80E-05	2.33487
163	0.323531	0.053	240.49	0.000137	2.383977
164	0.32725	0.054	226.34	0.000125	2.403951

Annex 4 Distribution of the leaching concentrations of the 1.57m² areas in the Wing-P field

The cumulative frequency distributions of the leaching concentrations of case 1 (Figure 6), were generated by dividing the 164 patch with variable areas in smaller areas of 1.57 m². Subsequently the number of 1.57 m² areas in a patch differ per patch. The leaching concentrations of the 1.57 m² areas are however not normally distributed. This is illustrated by the histograms shown below (Figure 10). The distribution of substance properties set 1 is positively skewed (i.e. the tail is more pronounced on the right side than it is on the left) and the distribution of substance properties set 2 is somewhat negatively skewed.

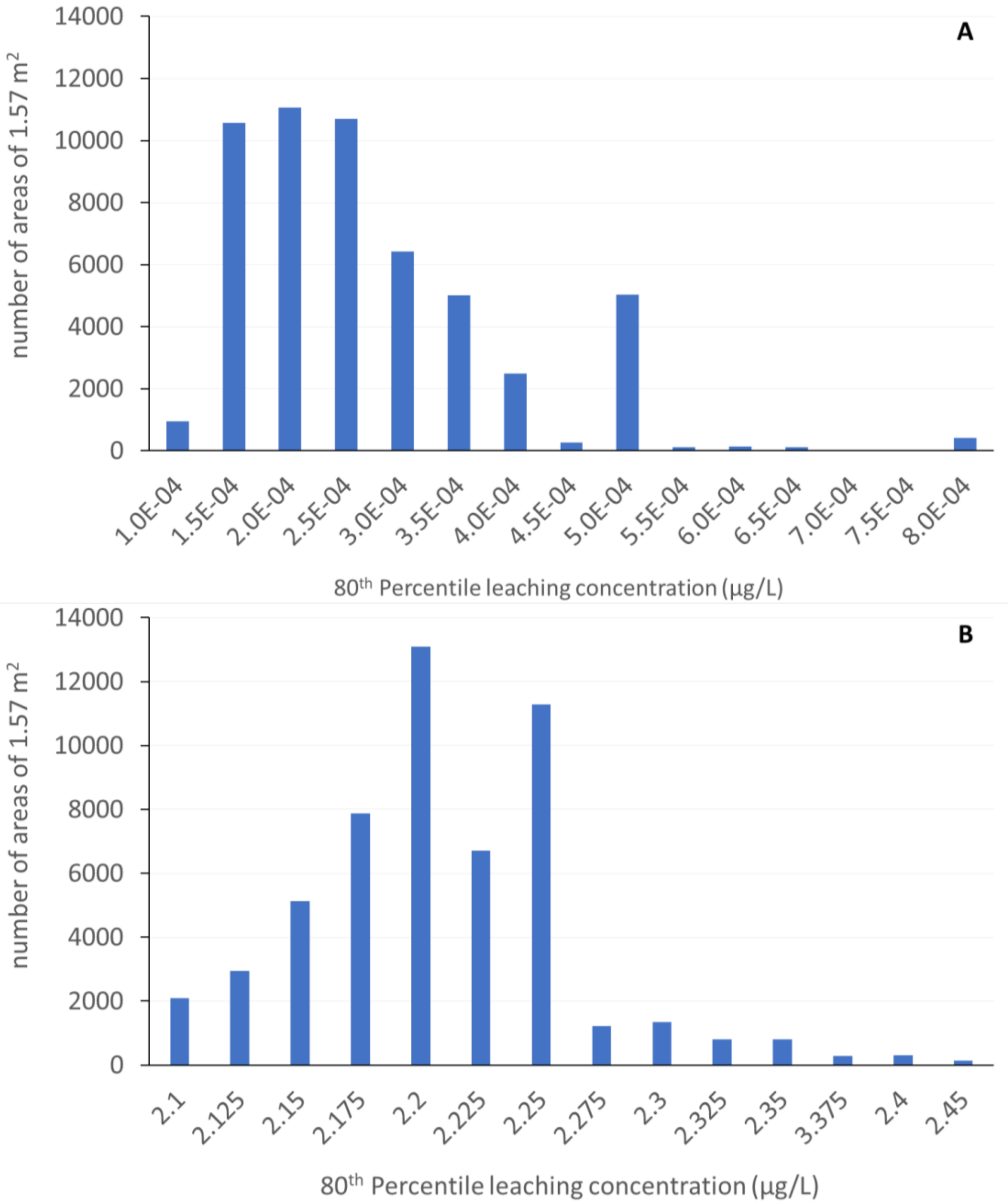

Figure 10 *Histograms showing the distribution leaching concentrations of the 1.57 m² areas for substance properties set 1 (graph A) and substance properties set 2 (graph B).*

Annex 5 Influence of the Freundlich coefficient on the leaching concentration

A third simulation using the default Freundlich coefficient of 0.9 (and thus assuming more non-linearity in sorption than in Set 1) was considered. However, a test simulation using the advised dose (4 L Wing-P/ha, so 0.85 kg a.i./ha) showed that the annual maximum leaching concentrations resulted in values below $9\ 10^{-5}$ µg/L and a 80^{th} percentile leaching concentration of $1\ 10^{-5}$ µg/L. Using dosages between the average of the specific minimum effective dose and the highest dose calculated from the task map resulted in even lower leaching concentrations, which led to the decision not to perform simulations for the 164 patches using a Freundlich coefficient of 0.9. Below it is explained why a lower Freundlich coefficient can lead to lower leaching concentrations.

In the PEARL model (Van den Berg et al., 2016) the sorption of non-dissociating pesticides on soil is described with a Freundlich-type equation. Part of the sorption is instantaneous (equilibrium sorption) and the other part proceeds only gradually (non-equilibrium sorption). For our simulations we assumed only equilibrium sorption. The equation for equilibrium sorption reads:

$$\boldsymbol{X_{eq} = K_{F,eq} \cdot c_{L,r} \left(\frac{c_L}{c_{L,r}}\right)^N} \qquad \textit{Eq. 3}$$

with:
X_{eq} = pesticide content in the equilibrium-sorption phase (kg kg^{-1})
$K_{F,eq}$ = Freundlich coefficient for the equilibrium-sorption phase (m^3 kg^{-1})
c_L = concentration in the liquid phase (kg m^{-3})
$c_{L,r}$ = reference concentration in the liquid phase (kg m^{-3})
N = Freundlich exponent (-)

A few simulations using the default Freundlich coefficient of 0.9 showed much lower leaching concentrations (about three magnitudes lower) than using the actual measured value for dimethenamid-P of 0.965. Figure 11 shows that compared to linear sorption, assuming Freundlich sorption can lead to relatively higher values of substance sorbed. This implies that less substance is found in the pore water of the soil and consequently less substance can leach to groundwater. This effect is larger for decreasing values of the Freundlich coefficient.

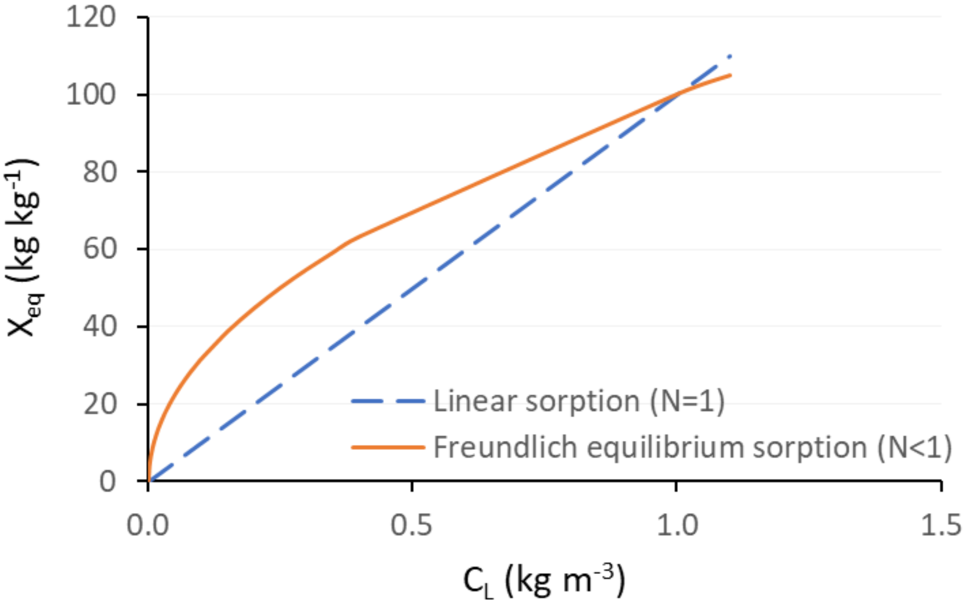

Figure 11 *Variation of X_{eq} with CL according to the Freundlich equilibrium sorption equation (Eq. 3; orange, solid line) and linear sorption (blue, dashed line, N=1 in Eq.3).*

Wageningen Environmental Research
P.O. Box 47
6700 AA Wageningen
The Netherlands
T 0317 48 07 00
wur.eu/environmental-research

Report 3293
ISSN 1566-7197

The mission of Wageningen University & Research is “To explore the potential of nature to improve the quality of life”. Under the banner Wageningen University & Research, Wageningen University and the specialised research institutes of the Wageningen Research Foundation have joined forces in contributing to finding solutions to important questions in the domain of healthy food and living environment. With its roughly 30 branches, 7,600 employees (6,700 fte) and 13,100 students and over 150,000 participants to WUR’s Life Long Learning, Wageningen University & Research is one of the leading organisations in its domain. The unique Wageningen approach lies in its integrated approach to issues and the collaboration between different disciplines.

To explore the potential of nature to improve the quality of life

Wageningen Environmental Research
P.O. Box 47
6700 AB Wageningen
The Netherlands
T +31 (0) 317 48 07 00
wur.eu/environmental-research

Report 3293
ISSN 1566-7197

The mission of Wageningen University & Research is "To explore the potential of nature to improve the quality of life". Under the banner Wageningen University & Research, Wageningen University and the specialised research institutes of the Wageningen Research Foundation have joined forces in contributing to finding solutions to important questions in the domain of healthy food and living environment. With its roughly 30 branches, 7,600 employees (6,700 fte) and 13,100 students and over 150,000 participants to WUR's Life Long Learning, Wageningen University & Research is one of the leading organisations in its domain. The unique Wageningen approach lies in its integrated approach to issues and the collaboration between different disciplines.