Effects of global change on the emission, fate, effects and risks of chemicals in aquatic ecosystems

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Deliverable D3.3 (D15): Chemical emission scenarios from pest management options under scenarios in selected agricultural systems

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1 Introduction

Climate change affects not only crop growing conditions and yield potential but also further abiotic and biotic damaging factors for crops. For example, potential yield alone for irrigated grain maize is projected to decline by more than 10% in southern Europe and production decreases by -18% (Deutsch et al., 2018, Feyen et al., 2020). Insect pests are one of the additional influencing drivers triggering ecological disturbances under climate change (CC) which in turn will boost their population density and increase their potential negative impacts on crops productivity. These developments create challenges for plant protection measures, including the use of chemicals and risks for increasing emissions from that source. In our study, we focus on main crops grown in Europe and related insect pests to demonstrate these effects on selected agro-ecosystems from a bottom-up approach. The related pests, European corn borer (ECB), western corn rootworm (WCR), and wireworms are economically important pests of maize and potatoes in central Europe. Agricultural production systems in Europe are additionally shifted spatially according to changes in temperature and precipitation patterns, where the predictability and amplitude of pest pressures remain unclear in the future. Climate change will negatively impact most regions across Europe (Olesen et al., 2011; Trnka et al., 2009; Eitzinger et al., 2013) in crop yields, soil fertility, pesticide use, and nutrient runoff. Grain maize and potato production are dominating agricultural activities in central and southern Europe and also move towards higher latitudes. Pesticides are currently the most common method to control weeds, pest, and fungal diseases. Problems with ECB, WCR, wireworms, weeds, and fungal diseases are likely to increase in future, production potential challenges for chemical emissions from pest management.

There are existing works to predict the pest population with likely impacts under CC scenarios. An integrated framework defining potential chemical emission risks from pest pressure-driven intensive cropping systems for the future projected climate change still requires a multi-disciplinary and bottom-up approach for more robust estimates.

2 Modelling approaches and development

2.1 Major aims, objectives and modelling components

The major aim of the Deliverable is to refine the existing approaches of deriving agricultural emission scenarios from pest management from a bottom-up approach based on regional climate impacts on pests and pest management options. The concept of the work is outlined in Figure 1 and described below.

I) Pest modelling development - The modelling work is done to simulate the pest life cycle for actual crop and weather conditions. The pest models derive methodology from the existing state of the art for the selected pests. Eventually, the outcome includes predicting population dynamics, spread/distribution (excluding wireworms), and the impact of climate change. The physiologically based pest models are calibrated and validated under past Austrian weather conditions. They are spatially explicit linked with GIS maps that predict spatiotemporal events and formulate management strategies options.

II) Develop the pest-specific regional scenarios and their assumptions based on the crop-pest management factors (pre-dominantly temperature and precipitation changes). These scenarios termed as 'chemical emission scenarios' are developed additionally from the existing regionalized climate model scenarios. The developed chemical emissions scenarios simulated from integrated cop-pest models and pesticide models will run under selected EUROCORDEX based RCP emission scenarios (see below).

To cover a transect of main climates from north to south of Europe, the regional CC impact studies (to demonstrate the ECB and WCR pressure conditions among other maize yield limiting factors (drought, effective global radiation)) will be conducted not only in central European conditions (case study Austria, see section 3), but also applied to two Northern and Southern European zones, respectively, under the CC scenarios for 2050.

III) Climate scenarios - Using Regional climate models (RCMs) projections through EURO-CORDEX (European-Coordinated Regional Climate Downscaling Experiment) based on CMIP5 (Coupled Model Intercomparison Project) Global climate models (GCMs). It provides regional climate projections of European zonal case studies (Norway, Austria, and Spain or South-eastern Europe) for theoretical pest dynamics at grid resolutions of 12 and 50 km. One of the primary objectives is to reproduce the present-day European temperature and precipitation climate gradient from north to south driving cropping and pest risks.

IV) Scenario synthesis – Shared Socioeconomic Pathways (SSP) will be linked with Euro-Agri-SSPs for a defined spatial extent (Austria) for the pest-specific pesticide scenarios in the final step. Additionally, the development of scenario uncertainty (stochastic and epistemic) framework table for inputs (data, drivers), models, linkages and decision support will be framed (Table 1). For this, existing and developed modelling concepts from the literature were surveyed.

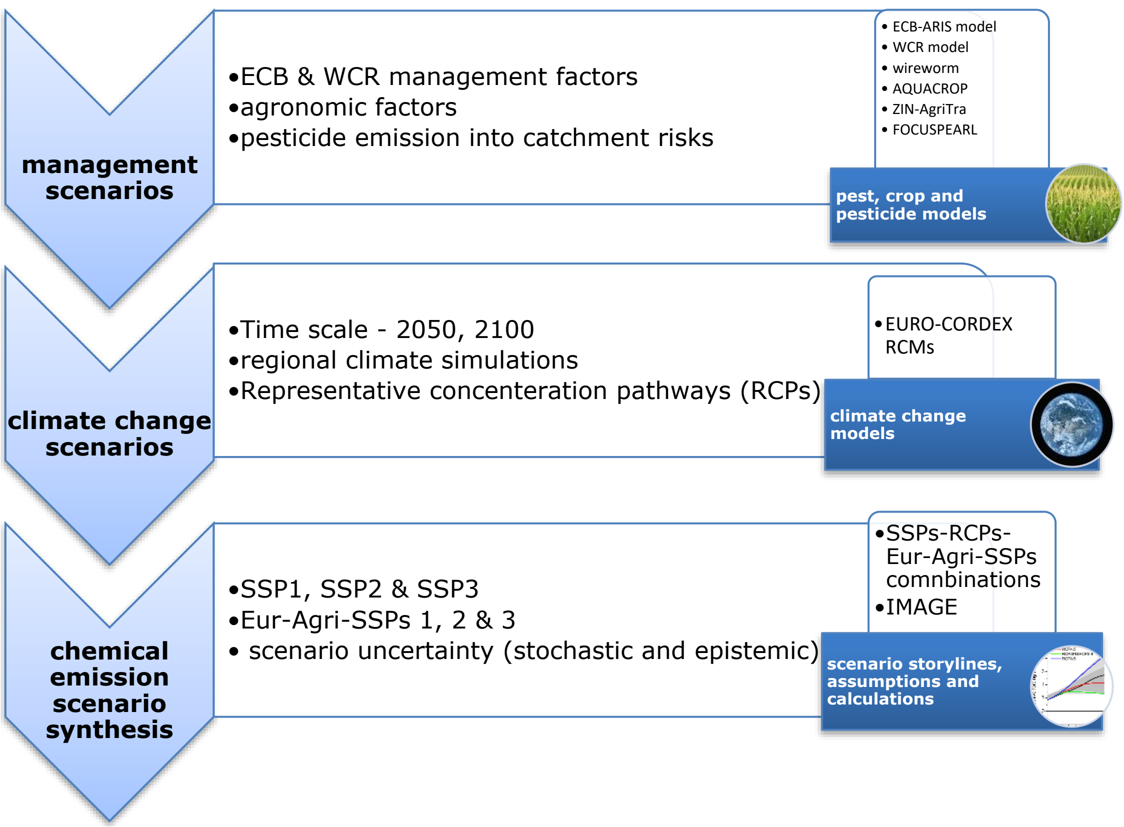

Figure 1 Scheme about the process of study

Calibrated pest model runs in Austrian conditions	EURO-CORDEX RCMs simulations	Emission scenarios (A2, B1) – climatic sensitivity (low, medium, high)		**SSP1 Sustaina bility**	**SSP2 Middle of the Road**	**SSP3 Regional Rivalry**	**Eur-Agr-SSP1 sustainable paths**	**Eur-Agri-SSP2 – established paths**	**Eur-Agri-SSP3 – separated paths**
			RCP2.6						
			RCP4.5						
			RCP8.5						

Table 1: Scenario-matrix architecture for pest-specific chemical emission scenarios

2.2 Literature survey

Since 1979, 70 studies have been shortlisted for deriving the existing modelling approaches (mainly empirical relationships) of selected pests (marked as yellow in Table 2), out of which 14 studies have assessed the impact of CC under different scenarios. The survey (Figure 2) includes quantitative (56), semi-quantitative (13), and qualitative (1) studies for modelling the pest development, spread and impact. Empirical models emerged earlier than process-based dynamic and mechanistic models, which excludes integration of complex interactions between pest, host plant, and environment.

Common name	**Species (Order: Family)**	**Major crops**
European corn borer	*Ostrinia nubialis* Hbn. (Lepidoptera: Crambidae)	Maize
Western corn rootworm	*Diabrotica virgifera virgifera* LeConte (Coleoptera: Chrysomelidae)	Maize, potato
Wireworms	*Agriotes* spp. (Coleoptera: Elateridae)	Maize, potato
Mediterranean corn borer	*Sesamia nonagrioides* Lefebvre (Lepidoptera: Noctuidae)	Maize
Cutworms	*Agrotis* spp. (Lepidoptera: Noctuidae)	Maize, turnips,
Cotton bollworm	*Helicoverpa armigera* Hbn. (Lepidoptera: Noctuidae)	Maize
European grapevine moth	*Lobesia botrana* (Lepidoptera: Totricidae)	grapevines
European grapeberry moth	*Eupoecilla ambiguella* Hbn. (Lepidoptera: Totricidae)	grapevines
Grape mealybugs	*Pseudococcus* spp. (Hemiptera: Pseudococcidae) *Planococcus ficus* (Hemiptera: Pseudococcidae)	grapevines
rape pollen beetle	*Meligethes aeneus* (Coleoptera: Nitidulidae)	oilseeds
Flea beetles		sugarbeet,
- cabbage stem	*Psylliodes chrysocephala* (Coleoptera: Chrysomelidae)	cruciferous
- rapeseed/sugarbeet	*Chaetocnema* spp. (Coleoptera: Chrysomelidae)	vegetables
Green peach aphid	*Myzus persicae* (Hemiptera: Aphididae)	grapevines
European red mite	*Panonychus ulmi* (Trombidiformes: Tetranychidae)	grapevines
American grapevine leafhopper	*Scaphoideus titanus* (Hemiptera: Cicadellidae)	grapevines

Table 2: Overview of critical pests from dominant cropping systems in Europe (in yellow are marked the target pests of our study).

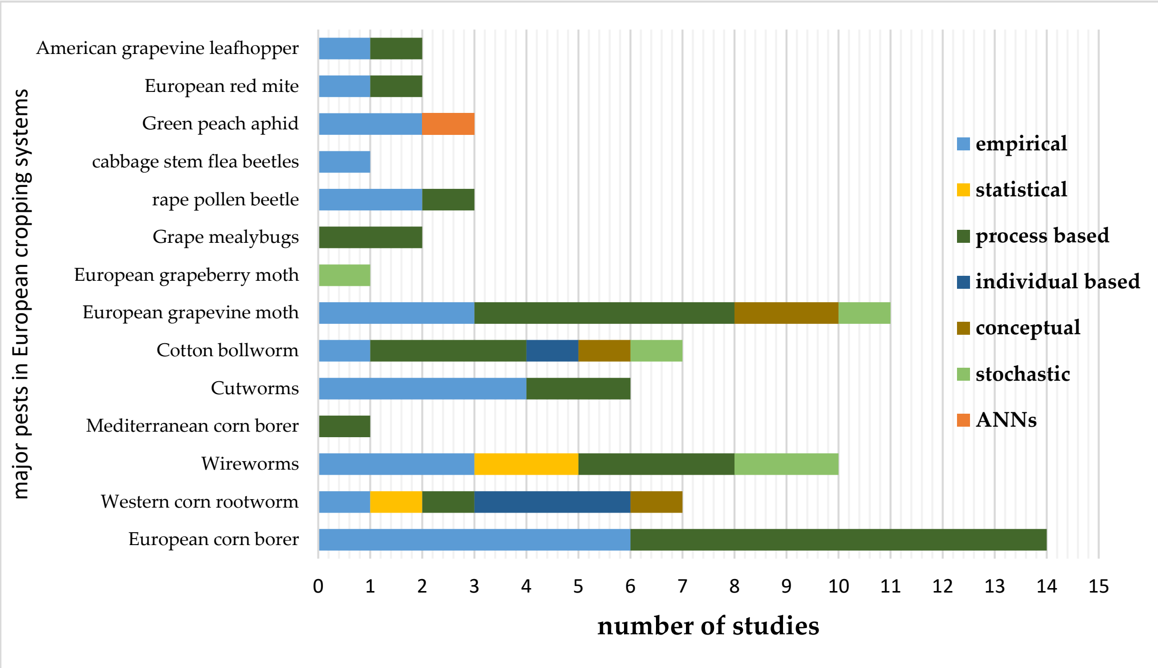

Figure 2. existing number of modelling studies in individual pests, globally

2.3 From insect pest occurrence to emission risks/impacts

The basic underlying concept for modelling the dynamics of pest, crop and pesticide behaviour in the soil and catchments of agricultural regions requires the connection of multiple simulation models (Figure 3). For each of the three pests in our study, an algorithmic workflow has been developed and programmed in the respective modelling environment.

The pest models are physiologically selective due to diverse complexities in terms of development rates, behaviour and damage patterns. Hence, the models require the development of individual components/modules as per the pest physiology and data availability (damage data for wireworms, adult catches for ECB and WCR). The models developed for ECB and WCR are physiologically based demographic models and aims to estimate the population in terms of larvae, adult and oviposition rates. The dispersal and survival components are under development following integration with spatial explicit indicator models of ARIS (Agricultural Risk Information system). The outcome generates the hotspot maps of selected locations with high resolution 1 km grid size in Austria.

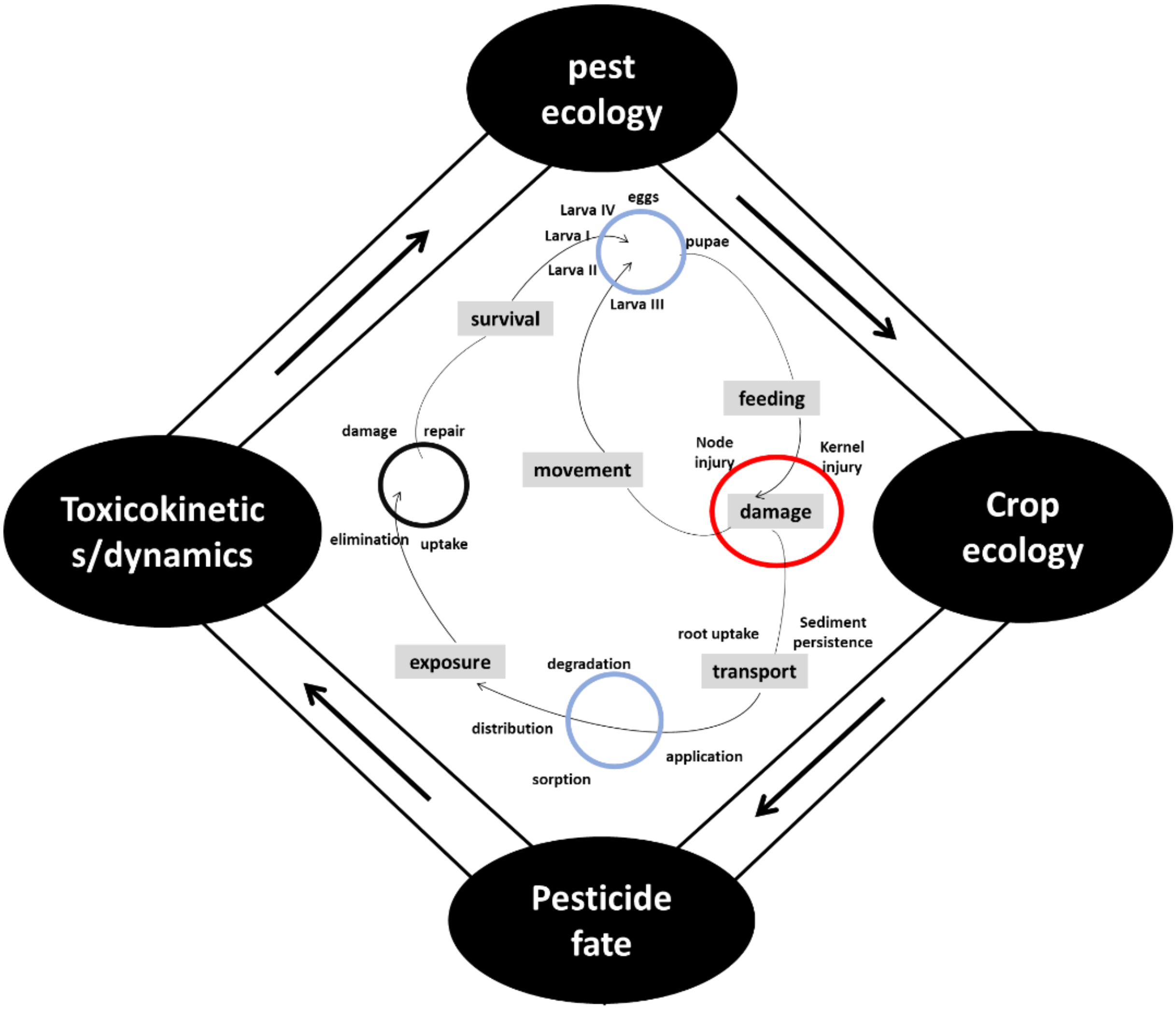

Figure 3. Modelling framework showing the primary processes and model connections.

The specific pest models and combinations applied in our study are described as follows:

2.3.1. European corn borer (ECB) - ARIS model

A process-based dynamic modular framework is developed in Eclipse IDE 4.18.0 Javascript, alongside API integration with R package and AQUACROP model. ECB-ARIS model derives state of methodology from the ECAMON model (Trnka et al., 2007) and ARIS model which is integrated to derive the grid based risk of population estimates in a given cropping system under the selected climate scenarios. The population estimates predicts the larval and adult abundance (in %), dates of diapause induction, flight activity (peak periods), and estimated generations in a year.

The model generates inputs of ECB geographical suitability in present climatic conditions and future climatic conditions for 2035 and 2050 based on the combination of A2 emission scenarios, sensitive climate, and General Circulation models (GCMs).

The example (Figure 4) of temperature and photoperiod dependent population model shows stage specific diapause simulation for a Baden weather station. The model is calibrated under all the weather stations of Austria following validation and testing.

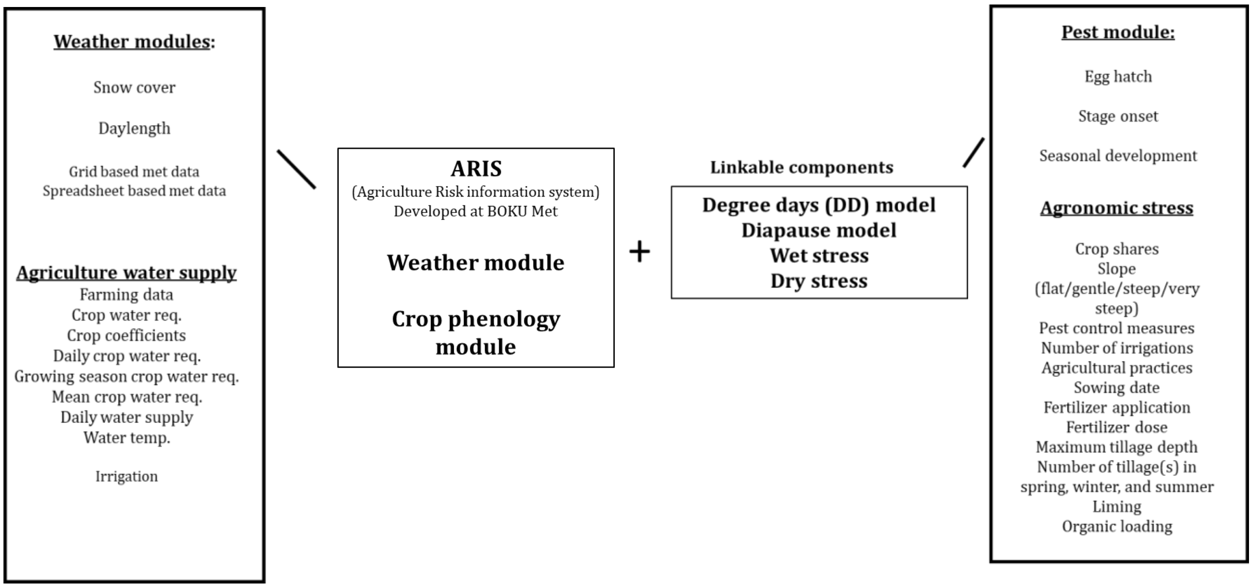

Figure 4. Workflow design of components integrated in ECB-ARIS model.

Sub models:

1. **Degree day (DD) model –** linear response relationship, empirically derives accumulated degree days to predict the life stages (eggs, 1-5 larval instars, pupa, and adults). Meteorological data are used, namely Mean daily temperature (MDT), minimum temperature (Tmin), maximum temperature (Tmax), peak temperature (Tpeak) and base temperature (Tbase).
   Tbase = 10 ◦C; Tmin < 0.2 ◦C for consecutive 3 days, ADD=0; Tmax > 32 ◦C, ADD=0

   if MDT < Tmin, then DD = 0,
   if MDT > Tmax, then DD = 0,
   if Tmax > MDT > Tpeak, then DD = Tpeak, and
   if Tpeak > MDT > Tmin, then DD = MDT − Tmin.

   $$\text{If } T_{max} < T_{base} \text{ then } DD = 0$$

   $$\text{If } T_{min} < T_{base} \text{ and } T_{max} > T_{base} \text{ then } DD = \left(\frac{T_{max} + T_{base}}{2}\right) - T_{base}$$

   $$\text{If } T_{min} > T_{base} \text{ then } DD = \left(\frac{T_{max} + T_{min}}{2}\right) - T_{base}$$

2. **Diapause model –** computes daylength hours in terms of scotophase (S) values using daylength model (to estimate the diapause and larval maturation) for Austrian latitudinal (L) value 47.6, mean air temperatures (T).

   $$D = -384 + 30.8S + 2.33T + 5.11L$$

3. **Stage specific onset model –** computes the predictive life stages on the basis of accumulated degree days (temperature thresholds defined by Brown et al., 1982 and Mason et al., 1996) and day length values.

An example of result from the above described life stage prediction model is shown in Figure 5.

The multiple regression models are still to be evaluated after the spatial analysis is done.

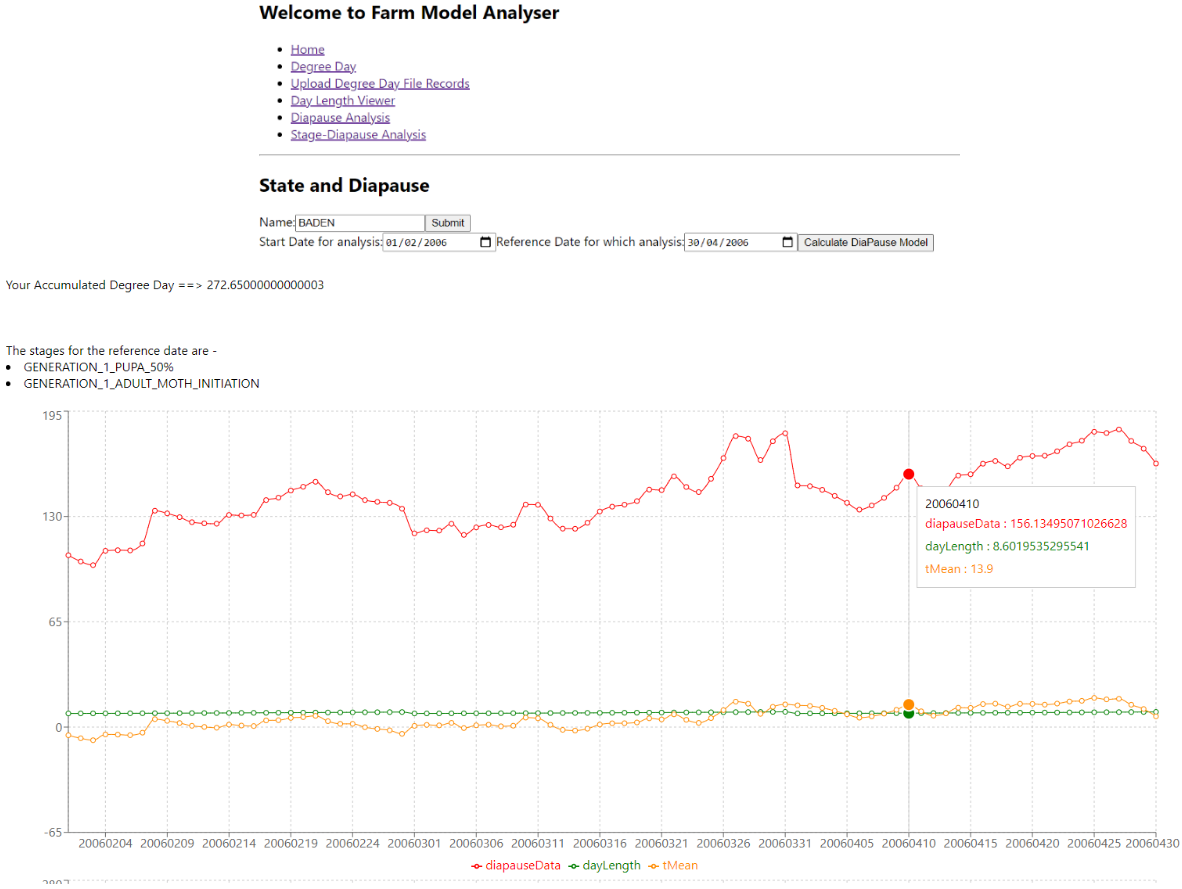

Figure 5. Life stage prediction of ECB and diapause requirements in a selected simulation period for Baden weather station.

2.3.2 Wireworm damage risk model

Associated ECORISK2050 partner MELES investigated, if the temperatures during an extended period in spring showed a more reliable relationship to wireworm damages (representative subsample for the years 2016 – 2019). Additionally, the aim was to design an independent variable in correspondence to known facts from wireworm biology, to enhance the interpretability of a resulting model. Data were collected in frame of ELATMON project (LKÖ/LFI), ELATMON 2019/2020, LE 14-20 M1a-198/19 and previous monitoring periods of the alert service (warndienst.at) of Agricultural Chamber, Austria, which is the second associated partner for this study within ECORISK2050.

For a first model approach, MELES summed up the soil temperatures (30 cm soil depth) between the days 60 – 176 (24th or 25th of June = around the beginning of *A. ustulatus* flight activity) that were higher than the development threshold of *Agriotes ustulatus* (ca. 9.5 °C; Furlan 1998), a dominant wireworm species in the region "Weinviertel". The soil temperatures showed a significant positive correlation with wireworm damages (Figure 6).

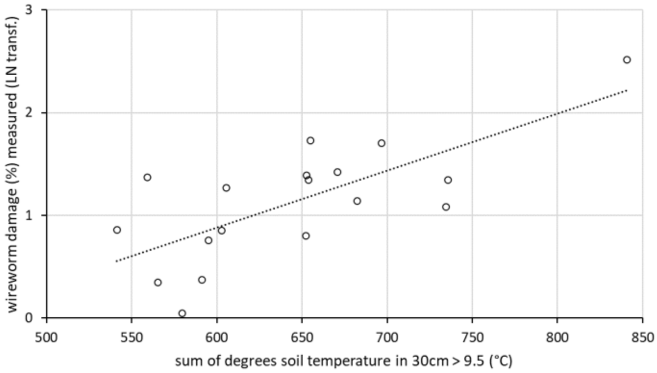

Figure 6. Relationship between soil temperatures in 30 cm (sum of temperatures > 9.5 °C between the days 60 - 176) and the measured wireworm damage data 2002 – 2019 (weight-% of delivered potatoes, LAPRO company, preliminary - data processing not finished yet)

Based on this relationship a new model approach was developed ("soiltemp.spring.model.1"). Since the soil temperatures between the days 60 and 176 were comparatively high in 2018 (red dashed line in Fig.7), the model simulates the excessive damage year 2018 correctly. However, for the years 2014 - 2017 the performance is currently low. This model approach will be further developed with temperature sums in other or additional periods and additional variables.

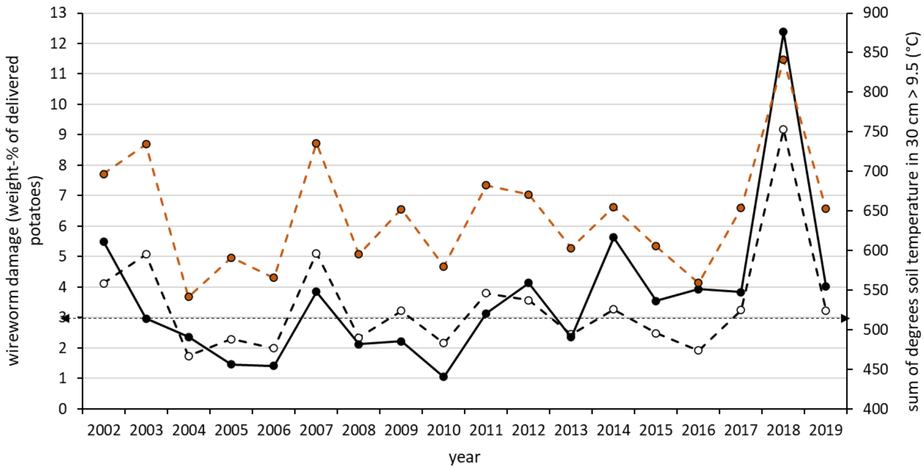

Figure 7. Model approach ("soiltemp.spring.model.1"), based on the soil temperatures in 30 cm (sum of temperatures > 9.5 °C between the days 60 - 176): black continuous line, filled circles = course of the measured mean wireworm damage level per year (weight-% of delivered potatoes, LAPRO company, preliminary - data processing not finished yet); black dashed line, empty circles = simulated values, the data of the whole period

2002 – 2019 were used for the development of the regression model ("soiltemp.spring.model.1"); red dashed line with orange filled circles: course of soil temperature > 9.5 °C in 30 cm soil depth (sum between days 60 – 176) = the independent variable, used in the model.

The third pest model applied in our study for the Western Corn Rootworm (WCR) is not further outlined here, and related details can be found in Falkner et al. (2020) and Agatz et al. (2017; 2020).

2.4 Scenario synthesis

2.4.1 Scenario characteristics

Goal and purpose: Derive extended European SSP1, SSP2 and SSP3 to EUR-Agri SSPs pesticide emissions in the aquatic environment/ catchments; provide a set of alternative future developments of the European agriculture and food systems where the pest pressure is a major driver; provide a refined set of plausible storylines and key uncertainties

Scenarios tailored to target groups: experts, stakeholders, non-profit organisations of climate change, ecotoxicity, chemistry, and social sciences sectors; policy makers in environmental agency, European agriculture and food systems; decision makers in the private sectors (supply chain managers)

Spatial scale: Regional case studies for the selected climate regions

Time scale – 2050, 2100

RCPs – 2.6, 4.5, 8.5

Type of scenario: qualitative and semi-quantitative storylines with trends (pesticide emission as a primary problem)

Storylines development: Chemical emission scenarios for the present study is defined as the key class of pesticides (primarily insecticides) emitted from the maize and potato systems into catchment ecosystems.

IMAGE scenarios "Global environmental change in the 21st century" are used for the combination of SSPs and RCPs as a baseline for scenario development. IMAGE projections are used for population, GDP, crop land, forest, pasture, and GHG emissions.

The scenarios combination is framed (see Table 1) to build a comparison between socio-economic sectors, agricultural sector, spatial and temporal scale under a defined global storyline.

2.4.2 Scenario assumptions and formulations: linking SSP scenarios to Eur-Agri-SSP scenarios

The global Shared socio-economic pathways (SSP1, SSP4, and SSP5) have been extended to link with three Euro-Agri SSPs (1,2 &3) which is stakeholder driven (Mitter et al., 2019; 2020). The spatial extent from the specific pests will be refined in our framework. Tables 3, 4, 5 represents the assumed scenario narratives across sectors with trends. Table 6 shows the key variables associated with formulation of management scenario assumption and Table 7 shows the pesticides under study in context with the investigated crops and pests.

Table 3: SSP drivers and trends (Mitter et al., 2019, 2020)

SSP drivers	SSPs sub-drivers	Possible impacts	narratives	Effects on pesticide emissions
Demographics	Popualtion growth	High population increase	Food demands effecting production following agricultural intensification	↗
	Urbanization	High urbanization	Food demands effecting production following agricultural intensification	↗
Human development	Education	Education based on practice	Awareness about pesticide residues and toxicity levels in food and water	↘
		Education access	Environmental impacts of pesticides leading to decreases usage	↘
Technology	Development	Specific management practices	Improved pesticide application methods, precision farming methods, Integrated pest management, forecasting tools	↗
		Specific cropping practices	Crop rotation methods, improved irrigation methods,	↗
		Breeding and molecular tool investments	Increased biotechnological tools for mycotoxins and pathogen resistant cultivars	↘
	Carbon intensity	Low	Less input/extensive farming (organic/extensive/subsistence farming)	↘
		High	high input/intensive farming (increased chemical emissions by pesticides and fertilisers)	↗
Agriculture	Changes in agricultural productivity	Average annual crop and forage yields	Pesticides and fertiliser costs	↗
	Changes in production costs	Changes in management techniques	Pesticides and fertiliser costs	↗
	Land-use	High cropland	Increased pesticide and fertiliser costs	↗
		Share of irrigated croplands	More irrigated water use with risk of increased transportability of nutrients and pesticides	↗
Climate change	Temperature	High temperature	Temperature increases pest outbreaks and thereby pesticides sales and use	↗

	Rainfall	High rainfall events	Rainfall increases pest outbreaks and thereby pesticides sales and use	↗
	Weather extremes	drought, hailstorms	Pest outbreaks	↗
Economic and lifestyle	Consumer diet preferences	Vegan/vegetarian diet	Reuced emissions by more land availability for organic and extensive cropping	⇨
		Meat	Increased methane and GHGs emissions and more forage crops production	↗
	Growth per capita (GDP) - Pesticide use	Agronomic development	Low input systems in developing and under-developed nations	↘
			high input systems in developed nations	↗
	International trade	High	Reduced trade barriers provide extra incentives for farmers to increase crop yields which could increase exports and pesticide use	↗
		Low	Reduced imports and reliance on self-produced food commodities	↘
Policies and institutions	Change in public expenditures (change in agricultural policy premiums)	Changes in management techniques	Average agricultural policy premiums	↘
	Institutions	Agricultural associations and institutes	Effective institutions could lead to decrease pesticide usage	↘
	International cooperation	Harmonized environmental standards	Regulation of environmental toxicity and risk assessment standards	↘

Table 4: cropping system drivers and risks

Crops	**Climate drivers**	**Narratives & risks**
Maize	Water stress	Increasing water demand
		Number of days with water deficit increases in spring
		Profound increase in summer drought duration
	Changes in phenology	Decrease in the number of suitable days for sowing
		Sowing dates moved forward
	More frequency of extreme events	Extreme Tmax events during grain filling
	Crop health	Population abundance of ECB resulting in increased damage
		Population abundance of WCR resulting in increased damage
		Increased mycotoxins in Maize by *Fusarium sp.*
	Farm management	Higher energy consumed in irrigation
		Complete loss or degradation of farming soils
		Seed treatment insecticides and more application sprays (granules in form of oil-dispersion and water-dispersable) of Tefluthrin, Thiacloprid, Acetamiprid, Indoxacarb, Clothianidin, Thiamethoxam.

	Ecosystem services	Reduction of ecosystem services or changes (pollination services, biodiversity loss, occurrence of invasive species)
Potato	Water stress	Number of days with water deficit increases in spring
		Number of days with water deficit increases in spring
		Higher demand for water, with probability of lower quality of irrigation water and nitrate pollution
	Farm management	Number of tillage operations between March and July
	Changes in phenology	Decrease in the number of suitable days for sowing
		Sowing dates moved forward
	More frequency of extreme events	Mean air temperature sums and precipitation in early spring seasons
		Soil temperatures in early spring
	Crop health	Wireworm abundance and damage

Table 5: Scenario development from management options for Maize and potatoes (also applied to Northern Europe and southern European regions)

management factors	Simulated region of the domain	CC scenario & time horizon	Trend (+/0/-)
Effective global radiation	central Europe	2050, 2100	+
Drought	central Europe	2050, 2100	+
ECB pressure	central Europe	2050, 2100	+
WCR pressure	central Europe	2050, 2100	+
Wireworm pressure	central Europe	2050, 2100	+
Irrigation, drainage	central Europe	2050	+
Pesticide	central Europe	2050	0

Table 6: Key variables associated with formulation of management scenario assumption (Appendix Table A.2)

Scenarios	Key variables for the narratives
Pest management scenarios	(i) Adult thresholds counts (ii) Range of damage probability (iii) Population growth rate in maize fields with pop. below 5 adults/plant (iv) Growing degree days (v) Seed treatment (rates), pesticide applications (kg/ha)
Crop-management scenarios	(i) % rotated maize (intra/inter annual schemes) (ii) % maize shares (iii) Weed abundance (iv) Temperature changes (v) Relative precipitation (vi) Organic matter > 5% (vii) Autumn ploughing & number of tillage operations season-wise (viii) Irrigation types (ix) Tile drain areas

Table 7: Selected pesticides under study, I- Insecticide, F – Fungicide, H - Herbicide

Active ingredient	type
Deltamethrin (I)	*Pyrethroid*
Lamba-cyhalothrin (I)	*Pyrethroid*
Tau-Fluvalinate (I)	*Pyrethroid*
Tefluthrin (I)	*Pyrethroid*
Cypermethrin (I)	*Pyrethroid*
Indoxacarb (I)	*Oxadiazine*
Thiacloprid (I)	*Neonicotinoid*
Acetamiprid (I)	*Neonicotinoid*
Chlorantraniliprole (I)	*Ryanoid*
Azoxystrobin (F)	Mitochondrial respiration inhibitor (systemic)
Fludioxonil (F)	Transport-associated glucose phosphorylation inhibitor (systemic)
Boscalid (F)	Carboxamide
Solatenol (F)	Carboxamide
Prothioconazole (F)	Demethylase enzyme inhibitor (systemic)
Metalaxyl (F)	Acylalanine
Thiabendazol (F)	Benzimidazole
Rimsulfuron (H)	ALS inhibitor
Terbuthylazine (H)	Triazine
Metolachlor (H)	Aniline (systemic)

The pesticide fate model is not outlined here, and study will be carried out after the soil analysis. Further output related parameters are listed in Appendix Table A.3

3 Details of the Central European region case study outlines, Austria

Soil analysis and study locations

Soil analysis at 0-5 cm for tracing selected pesticide contaminants is carried out for current growing calendar 2021 using liquid chromatograph HPLC with optical and mass detectors LC-MS / MS.

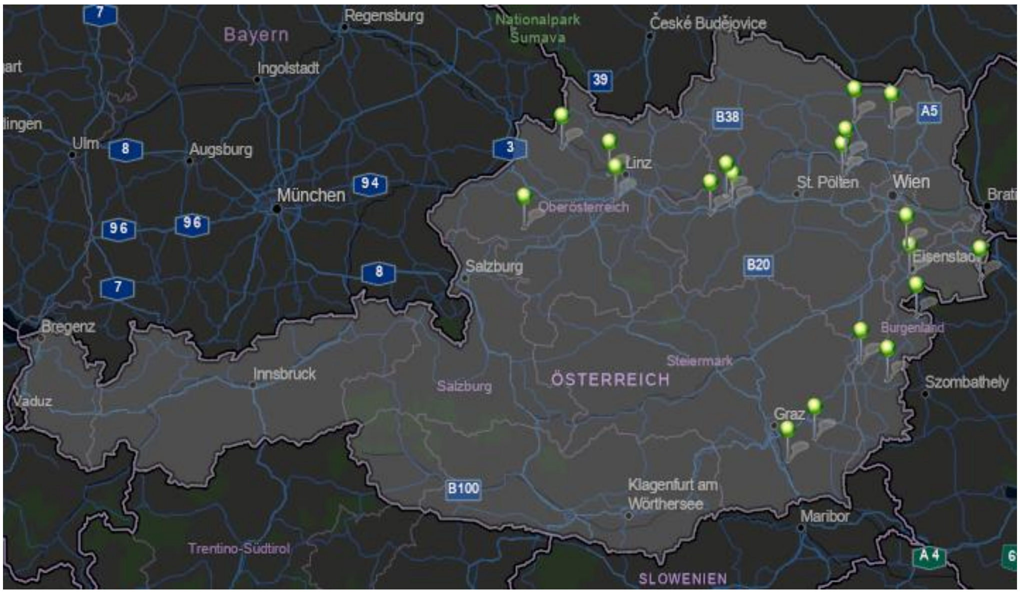

Figure 8. Selected regions (marked in green tip) for soil sediment collections

In total, 19 key districts (Figure 8, Appendix A1) of Austria are selected based on crop shares and observed pest occurrences with the help of monitoring data of Western corn root worm (WCR) and wireworm, respectively. Data sources are based on ELATMON project (LKÖ/LFI), ELATMON 2019/2020, LE 14-20 M1a-198/19 and previous monitoring periods of the alert service (warndienst.at) of Agricultural Chamber, Austria. An example of the Wulka catchment from Burgenland state is shown (Figure 9) as one of the catchment scale studies for WCR. The map-based watershed downstream and slope classification has been done for selection of soil samples, three times a season (pre, during and post-harvest). The soil analytical parameters for selected pesticides will be tested in the current year 2021 for maize and potato seasons at the lab unit of the Institute of Soil Research, BOKU.

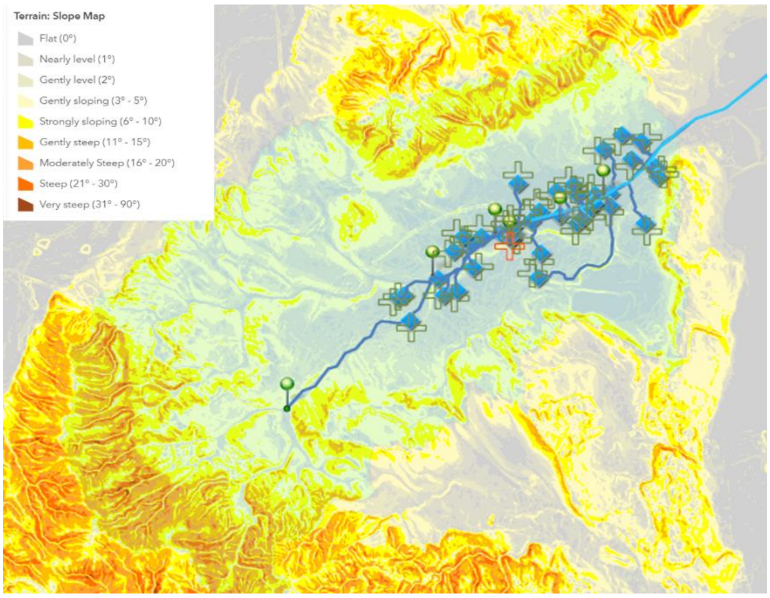

Figure 9. Catchment scale maps with downstream marked watersheds generated for field soil sampling.

4 Summary

The improved pest modelling approach integrated with CC impact under emission scenarios provides a reasonable basis for further discussion and development of advanced crop protection strategies with reduced input of chemical pesticides in European maize and potato production. This also enables the extension of future changes in species sensitivity and data uncertainty analysis for more refined assessments and targeted management of ecological risks under future scenarios.

A generic modelling approach for the quantitative analysis of spread and invasion risks requires more efforts by insect ecologists. This will facilitate the development of specific pest risk analyses (PRA). These models should be trained with data from climate and agricultural models and other available information.

Multiple models with uncertainties across scales requires joint efforts from social scientists, environmental scientists, decision makers, policy experts to formulate an improved risk assessment for pest and pesticides. Emission scenarios for pesticides from agricultural systems bring the uncertainty discussions to the table to fill the gap of socio-economic drivers (qualitative) and bio-physical drivers (quantitative). Application of Eur-Agri-SSPs have the potential to provide quantitative assumptions into existing SSPs. This way, they will help extend the SSPs to a specific pest-driven pesticide emission scenario development for the future at a national and local scale.

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Appendix

Table A.1 regional districts under observation for cropping and pest risks

S.no.	Selected regions along 5 federal states
1	Pixendorf, Lower Austria
2	Phyra, Lower Austria
3	Zwettl, Lower Austria
4	Leutzmannsdorf, Lower Austria
5	Ernstbrunn, Lower Austria
6	Hollabrunn, Lower Austria
7	Tulln, Lower Austria
8	Schönering, Upper Austria
9	Ratzling, Upper Austria
10	Zipf, Upper Austria
11	Sipbach, Upper Austria
12	Wulka, Burgenland
13	Rustenbach, Burgenland
14	Leitha, Burgenland
15	Pinka, Burgenland
16	Podler, Burgenland
17	Andau, Burgenland
18	Kirchberg, Styria
19	Stiefing, Styria

Table A.2 Overview of explanatory variables used in pest models (including qualitative and quantitative)

Variables	Description	Type
Climatic		
Mean rainfall	Given days before sowing	Quantitative
Cumulative rainfall	Between sowing and leaf stages	Quantitative
Mean soil temperature	Number of days before sowing, post-sowing, and between growth stages	Quantitative
Soil characteristics		
Soil texture	Clay/loam/sand/silt	Qualitative
Organic matter content	Proportion	Quantitative
pH		Quantitative
Root depth		Quantitative
Field capacity	< 70 mm, 70-120 mm, 120-170 mm, > 170 mm	Quantitative
Water sensitivity		Qualitative
Field configuration	Non-drained/ drained / hydromorphic	
Topography		Qualitative
Exposition	Flat/slope	Qualitative
Agricultural practices	N/S/E/W	
Sowing date		Quantitative
Fertilizer application		Quantitative
Fertilizer dose	Yes/no	Quantitative
Maximum tillage depth		Quantitative
Number of tillage(s) in spring, winter, and summer		Quantitative
Liming		Quantitative
Organic loading		Quantitative
Pest monitoring		

presence and identification of predominant species ***Past practices*** Number of irrigations Major tillage type Number of organic loadings ***Field history*** Historic of meadows in the field Rotation type Type of intercrop ***Landscape context*** Wooden hedgerow Vegetal hedgerow Presence of an adjacent crop Presence of an adjacent culture with a separation Presence of an adjacent meadow Presence of an adjacent meadow with a separation Grass strip ***Crop protection*** Chemical protection against pests:	 yes	Qualitaitve Quantitative Qualitaitve Quantitative Qualitaitve Qualitaitve Qualitaitve Qualitaitve Qualitaitve Qualitaitve Qualitaitve Qualitaitve Qualitaitve Qualitaitve Qualitaitve Qualitaitve Semi- quantitative

Table A.3 Pesticide fate model

Zin-AgriTRA model for a selected catchment region compute the pesticide and their two transformed products (TP1 and TP2) in soil and river (concentrations). It produces daily output time series of the channel routing, soil and water balance.

Soil timeseries outputs
1. "Date/Time"
2. "Rainfall": Amount of rainfall in the time step(mm)
3. "Evap(mm)": Amount of evapotranspiration in the time step
4. "Soilmoisture_1": Soil moisture of layer 1.
5. "Soilmoisture_2": Soil moisture of layer 2.
6. "Soilmoisture_3": Soil moisture of layer 3.
7. "MacroMoisture_1": Relative filling of the macroporosity of layer 1.
8. "MacroMoisture_2": Relative filling of the macroporosity of layer 2.
9. "MacroMoisture_3": Relative filling of the macroporosity of layer 3.
10. "Water_Column": Depth of the water column (mm).
11. "SSY(kg)": Amount of suspended sediment in the water column.
12. "DP_soil(mg/l)": Dissolved phosphorus concentration in soil layer 1 (mg/l).
13. "PP_soil(g/kg)": Particulate phosphorus concentration in soil layer 1 (g/kg).
14. "PinBiomass(kg/ha)": Amount of phosphorus in biomass (kg/ha).
15. "Biomass(kg/ha)": Amount of biomass in cell (kg/ha).
Pesticide timeseries outputs in soil
1. "Date/Time"
2. "DPest_plant(g/m2)": Dissolved substance at the plant surface (g/m2).
3. "Pest_mixing_layer(mg)": Amount in the mixing layer (mg/cell).
4. "DPest_soil_1(µg/l)": Dissolved substance concentration in soil layer 1 (µg/l).

5. "DPest_soil_2(μg/l)": Dissolved substance concentration in soil layer 2 (μg/l).
6. "DPest_soil_3(μg/l)": Dissolved substance concentration in soil layer 3 (μg/l).
7. "PPest_soil_1(mg/kg)": Adsorbed substance concentration in soil layer 1 (mg/kg).
8. "PPest_soil_2(mg/kg)": Adsorbed substance concentration in soil layer 2 (mg/kg).
9. "PPest_soil_3(mg/kg)": Adsorbed substance concentration in soil layer 3 (mg/kg).
10. "DPest_OF(μg/l)": Dissolved substance concentration in overland flow (μg/l).
11. "PPest_OF(mg/kg)": Adsorbed substance concentration in overland flow (mg/kg).
Water balance outputs
1. ModelRun:Date/Time: Date and time when the model run took place.
2. sim-Day Rain(mm): Date simulated by the model.
3. Evap(mm): Actual evapotranspiration sum (mm).
4. GW_recharge(mm): Sum of water leaving the third soil layer towards the bedrock (mm).
5. storage_change(mm): Storage change in soil and interception storage (mm).
6. WaterColChange(mm): Amount of water storage change in overland flow (mm).
7. exfiltration(mm): Amount of water leaving the first soil layer towards overland flow (mm).
8. OFlowToRiver(mm): Amount of overland flow reaching the river (mm).
9. MatrixflowToRiver(mm): Amount of soil matrix flow reaching the river (mm).
10. MacroporeflowToRiver(mm): Amount of soil macropore flow reaching the river (mm).
11. DrainageflowToRiver_Matrix(mm): Amount of soil matrix flow reaching tile drains (mm).
12. DrainageflowToRiver_Macro(mm): Amount of soil macropore flow reaching tile drains (mm).
13. Q_Outlet(mm): Amount of water leaving the catchment (mm).
14. Sed_Outlet(t/ha): Amount of suspended sediment leaving the catchment (t/ha).
15. PP_Outlet(kg/ha): Amount of adsorbed phosphorus leaving the catchment (t/ha).
16. DP_Outlet(kg/ha): Amount of dissolved phosphorus leaving the catchment (t/ha).
17. Balance-Error: Water balance error due to rounding or numerical errors (mm).
Pesticide balance and daily fate (including transformed products)
1. ModelRun:Date/Time: Date and time when the model run took place.
2. sim-Day: Date simulated by the model.
3. Pest_Outlet(g/ha): Mass of Pest leaving the catchment.
4. TP1_Outlet(g/ha): Mass of TP1 leaving the catchment.
5. TP2_Outlet(g/ha): Mass of TP2 leaving the catchment.
6. Pest_ChanRest(g/ha): Mass of Pest currently in the river channel.
7. TP1_ChanRest(g/ha): Mass of TP1 currently in the river channel.
8. TP2_ChanRest(g/ha): Mass of TP2 currently in the river channel.
9. Pest_MixingLayer(g/ha): Mass of Pest in the mixing layer.
10. TP1_MixingLayer(g/ha): Mass of TP1 in the mixing layer.
11. TP2_MixingLayer(g/ha): Mass of TP2 in the mixing layer.
12. Pest_Soil(g/ha): Sum of Pest in all three soil layers.
13. TP1_Soil(g/ha): Sum of TP1 in all three soil layers.
14. TP2_Soil(g/ha): Sum of TP2 in all three soil layers.
15. Pest_Plant(g/ha): Mass of Pest at the plant surface.
16. TP1_Plant(g/ha): Mass of TP1 at the plant surface.
17. TP2_Plant(g/ha): Mass of TP2 at the plant surface.
18. Pest_OF(g/ha): Mass of Pest in overland flow.
19. TP1_OF(g/ha): Mass of TP1 in overland flow.
20. TP2_OF(g/ha): Mass of TP2 in overland flow.
21. Pest_inf(g/ha): Mass of Pest infiltrated into the soil.
22. TP1_inf(g/ha): Mass of TP1 infiltrated into the soil.
23. TP2_inf(g/ha): Mass of TP2 infiltrated into the soil.
24. Pest_degraded(g/ha): Mass of Pest transformed/degraded.
25. TP1_degraded(g/ha): Mass of TP1 transformed/degraded.

26. TP2_degraded(g/ha): Mass of TP2 transformed/degraded.
27. Mineralization(g/ha): Mass of substance mineralized.
28. Pest_rock_inf(g/ha): Mass of Pest leaving the 3rd soil layer towards the bedrock.
29. TP1_rock_inf(g/ha): Mass of TP1 leaving the 3rd soil layer towards the bedrock.
30. TP2_rock_inf(g/ha): Mass of TP2 leaving the 3rd soil layer towards the bedrock.
31. Pest_MacroRiver(g/ha): Mass of Pest reaching the river via macropores.
32. TP1_MacroRiver(g/ha): Mass of TP1 reaching the river via macropores.
33. TP2_MacroRiver(g/ha): Mass of TP2 reaching the river via macropores.
34. Pest_MatrixRiver(g/ha): Mass of Pest reaching the river via soil matrix.
35. TP1_MatrixRiver(g/ha): Mass of TP1 reaching the river via soil matrix.
36. TP2_MatrixRiver(g/ha): Mass of TP2 reaching the river via soil matrix.
37. DPest_OFRiver(g/ha): Mass of dissolved Pest reaching the river via overland flow.
38. DTP1_OFRiver(g/ha): Mass of dissolved TP1 reaching the river via overland flow.
39. DTP2_OFRiver(g/ha): Mass of dissolved TP2 reaching the river via overland flow.
40. PPest_OFRiver(g/ha): Mass of adsorbed Pest reaching the river via overland flow.
41. PTP1_OFRiver(g/ha): Mass of adsorbed TP1 reaching the river via overland flow.
42. PTP2_OFRiver(g/ha): Mass of adsorbed TP2 reaching the river via overland flow.
43. PestDrainage_Matrix(g/ha): Mass of Pest reaching the river by soil matrix flow to tile drains.
44. TP1Drainage_Matrix(g/ha): Mass of TP1 reaching the river by soil matrix flow to tile drains.
45. TP2Drainage_Matrix(g/ha): Mass of TP2 reaching the river by soil matrix flow to tile drains.
46. PestDrainage_Macropore(g/ha): Mass of Pest export to the river by macropore flow to tile drains.
47. TP1Drainage_Macropore(g/ha): Mass of TP1 reaching the river by macropore flow to tile drains.
48. TP2Drainage_Macropore(g/ha): Mass of TP2 reaching the river by macropore flow to tile drains.
49. PestApplication(g/ha): Mass of Pest applied in the catchment.