

Key challenges in linking pesticide application and mitigation techniques to effect risk assessment: a focus on atmospheric processes contribution

XVIII SYMPOSIUM ON PESTICIDE CHEMISTRY
“Next generation solutions and sustainable frontiers”, Cremona (Italy)

Session
New frontiers in pesticide science: linking application technology, exposure and effect risk assessment

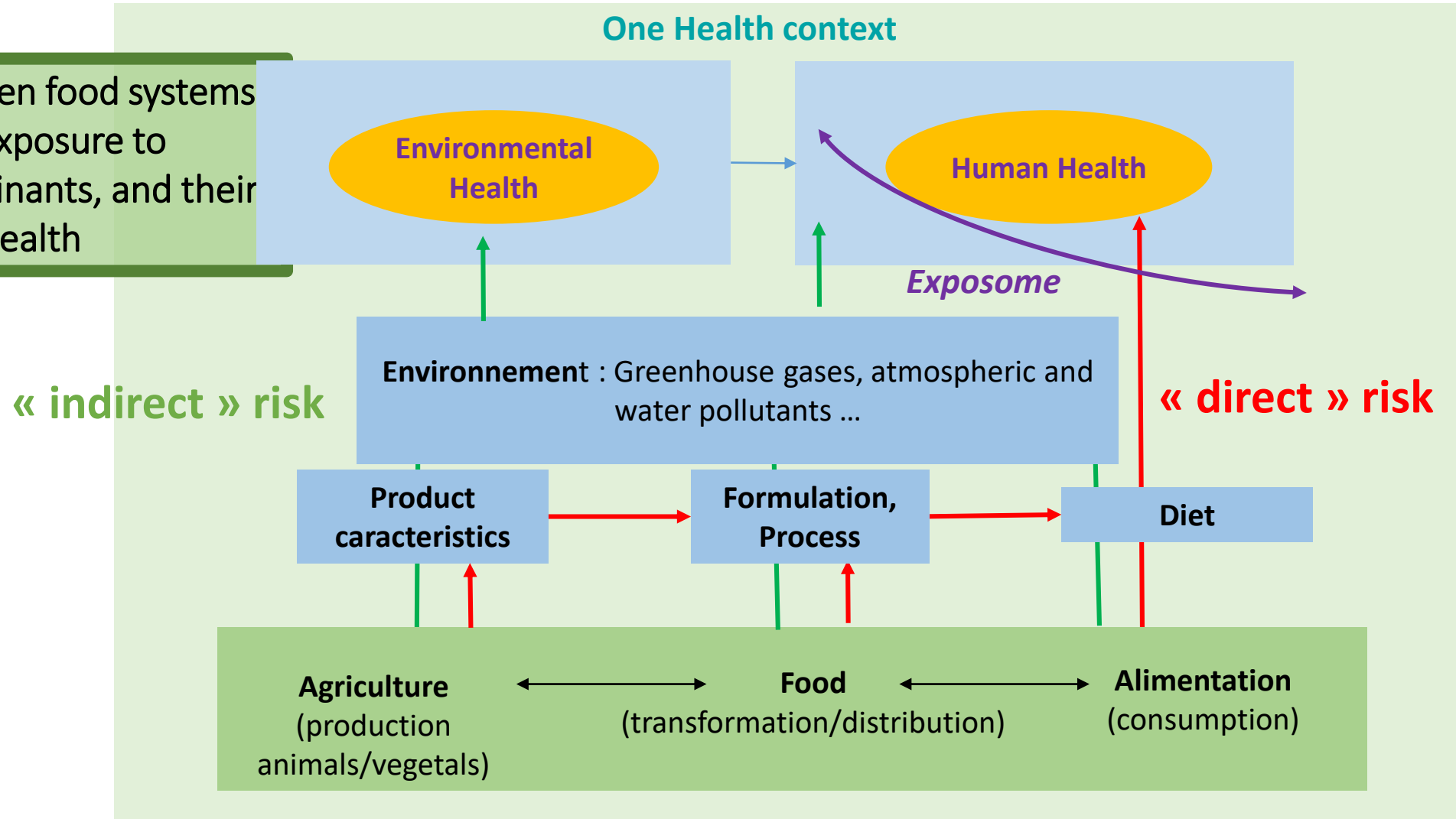
Carole BEDOS

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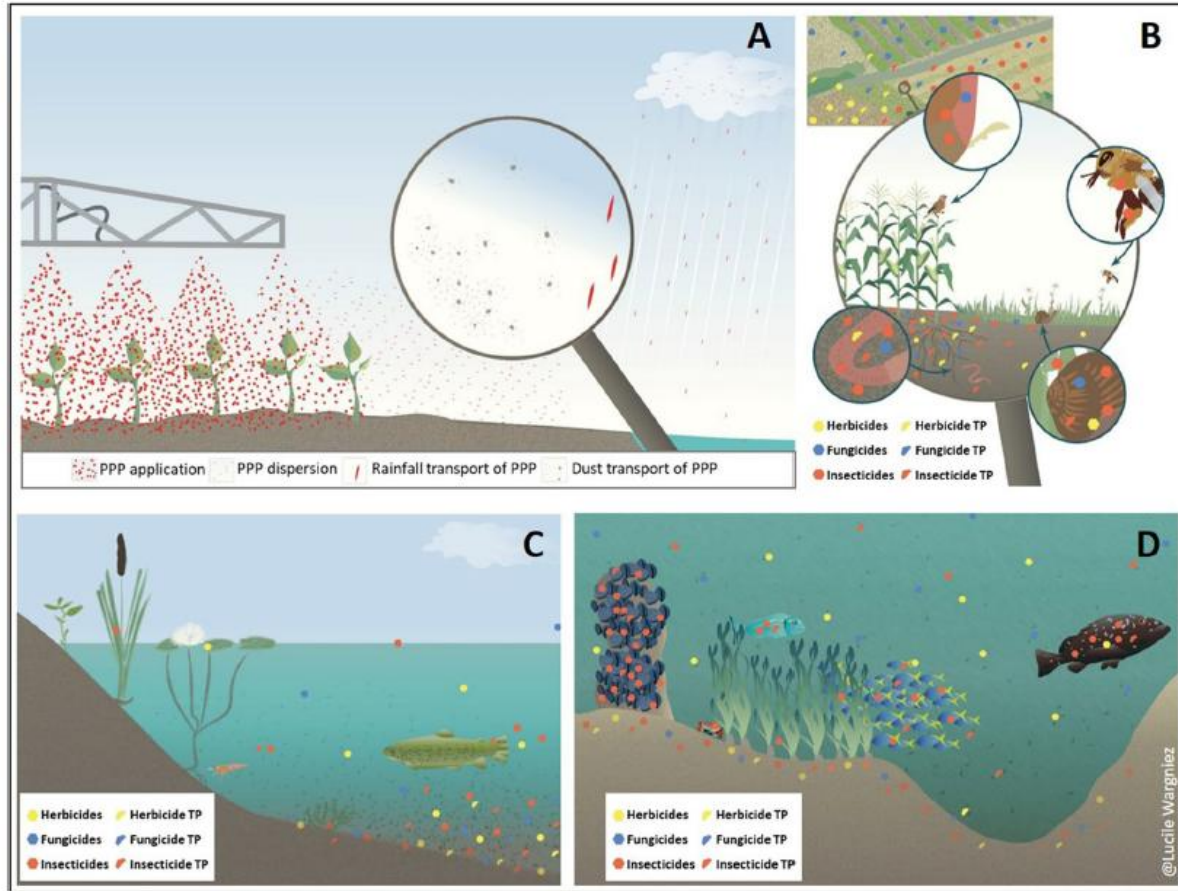
And colleagues

Context : food systems & environmental pollutants & health

Challenge : Link between food systems and population exposure to environmental contaminants, and their impact on health



Context : contamination of all environmental compartments & exposure



Contamination of:

- Continental and marine aquatic environments (living matter, sediments, transitional and coastal waters)
 - Soil
 - Atmosphere
 - Terrestrial, aquatic and aerial biota
- => **Exposure** of ecosystems and human population

Fig.2 Schematic illustration of the distribution of contamination by plant production products (PPP) and their transformation products (TP) in different matrices (including biota) in **A** the atmosphere and in **B** terrestrial, **C** freshwater and **D** marine environments

Context : contamination of all environmental compartments but with specific features

A comparative overview of maximum concentrations for the 33 substances most frequently detected in at least one environmental compartment (France)*

- ⇒ Over the 33 a.i.: 5 insecticides, 9 fongicides, 15 herbicides, 4 transformation products
- ⇒ Different fates

*based on 70 studies for soil, 82 for freshwater, 81 for seawater and the Phytatmo database for air – data from 2010 onwards

substance	family	year of ban (France)	maximum concentration levels in environmental matrices			
			soil	freshwater	marine water	air
azoxystrobin	fungicide	-				
boscalid	fungicide	-				
chlorothalonil	fungicide	2020				
epoxiconazole	fungicide	2019				
fenpropidin	fungicide	-				
folpet	fungicide	-				
prochloraz	fungicide	2022				
spiroxamine	fungicide	-				
tebuconazole	fungicide	-				
acetochlor	herbicide	2013				
alachlor	herbicide	2008				
atrazine	herbicide	2003				
chlortoluron	herbicide	-				
disflufenican	herbicide	-				
diuron	herbicide	2008				
glyphosate	herbicide	-				
isoproturon	herbicide	2017				
metolachlor	herbicide	2004 (except for s-metolachlor)				
pendimethalin	herbicide	-				
prosulfocarb	herbicide	-				
simazine	herbicide	2003				
terbutylazine	herbicide	2004 (with some exemptions)				
terbutryn	herbicide	2003				
triallate	herbicide	-				
AMPA	herbicide TP	(TP)				
atrazine deisopropyl (DIA)	herbicide TP	(TP)				
atrazine desethyl (DEA)	herbicide TP	(TP)				
DCPMU	herbicide TP	(TP)				
chlordecone	insecticide	1993				
chlorpyrifos ethyl	insecticide	2020				
chlorpyrifos methyl	insecticide	2022				
imidacloprid	insecticide	2018 (with some exemptions)				
lindane	insecticide	1998				

Fig.2 Schematic illustration of the distribution of contamination by plant production products (PPP) and their transform different matrices (including biota) in A the atmosphere and in B terrestrial, C freshwater and D marine environments

Margum et al. (2025)

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concentration ranges in all matrices	not recorded	not recorded	not recorded	not recorded
	C < 1 ng.g ⁻¹	C < 1 ng.L ⁻¹	C < 1 ng.L ⁻¹	C < 0.1 ng.m ⁻³
	1 < C < 10 ng.g ⁻¹	1 < C < 10 ng.L ⁻¹	1 < C < 50 ng.L ⁻¹	0.1 < C < 1 ng.m ⁻³
	10 < C < 100 ng.g ⁻¹	10 < C < 100 ng.L ⁻¹	50 < C < 200 ng.L ⁻¹	1 < C < 10 ng.m ⁻³
	100 < C < 1000 ng.g ⁻¹	100 < C < 1000 ng.L ⁻¹	200 < C < 500 ng.L ⁻¹	10 < C < 100 ng.m ⁻³
	1000 < C < 10000 ng.g ⁻¹	C > 1000 ng.L ⁻¹	C > 500 ng.L ⁻¹	C > 100 ng.m ⁻³
	C > 10000 ng.g ⁻¹			

Context : different contamination levels – case of the atmosphere

Background contamination vs Local contamination

(sampling at distances > ~ 100m from any treated fields)

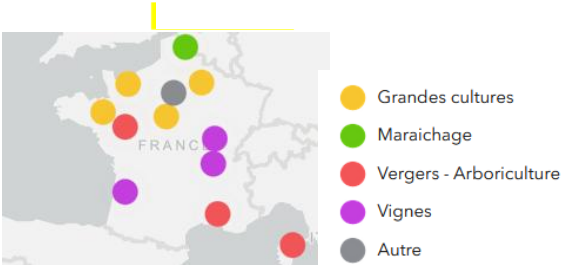
Monitoring of the gaz/particle concentrations: a French national long-term monitoring (SPN)

2021-2022 (18 locations, 75 substances)

← Increasing mean annual concentration (ng/m³)

≥ 1 ng/m ³	≥ 0,5 ng/m ³	≥ 0,2 ng/m ³	≥ 0,1 ng/m ³	≥ 0,05 ng/m ³	≥ 0,02 ng/m ³	≥ 0,01 ng/m ³
1 substances	1 substances	2 substances	4 substances	6 substances	11 substances	14 substances
Prosulfocarbe	Prosulfocarbe	Prosulfocarbe	Prosulfocarbe	Prosulfocarbe	Prosulfocarbe	Prosulfocarbe
		Pendimethaline	Pendimethaline	Pendimethaline	Pendimethaline	Pendimethaline
			Triallate	Triallate	Triallate	Triallate
			Folpel	Folpel	Folpel	Folpel
				Fenpropidine	Fenpropidine	Fenpropidine
				Lindane	Lindane	Lindane
				Spiroxamine	Spiroxamine	Spiroxamine
				Pyrimethanil	Pyrimethanil	Pyrimethanil
				Chlorpyriphos methyl	Chlorpyriphos methyl	Chlorpyriphos methyl
				Metolachlore(-s)	Metolachlore(-s)	Metolachlore(-s)
				Propyzamide	Propyzamide	Propyzamide
				Fluopyram		Fluopyram
				Glyphosate		Glyphosate
				Permethrine		Permethrine

QF>20%



Dataviz : <https://storymaps.arcgis.com/stories/b5e04945978c4b0f876398812330d330>



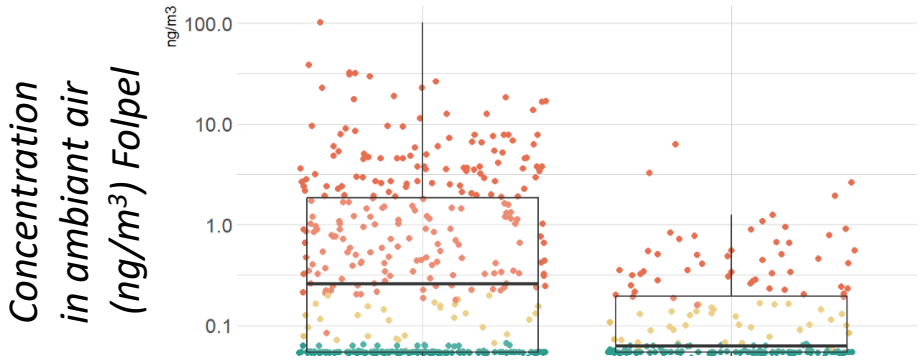
(sampling from 15m to 86m of vineyards)
Resident exposure: the French PestiRiv national campaign
Comparison of wine-growing areas vs far from any crops
(6 vineyard regions, oct 2021 –August 2022, 56 substances)



- ✓ ambient air & indoor air
- ✓ Indoor dust
- ✓ residents' hair and urine
- ✓ garden products

Across all sample categories, exposure is :

- Higher in wine-growing areas than far from any crops



wine-growing areas far from any crops

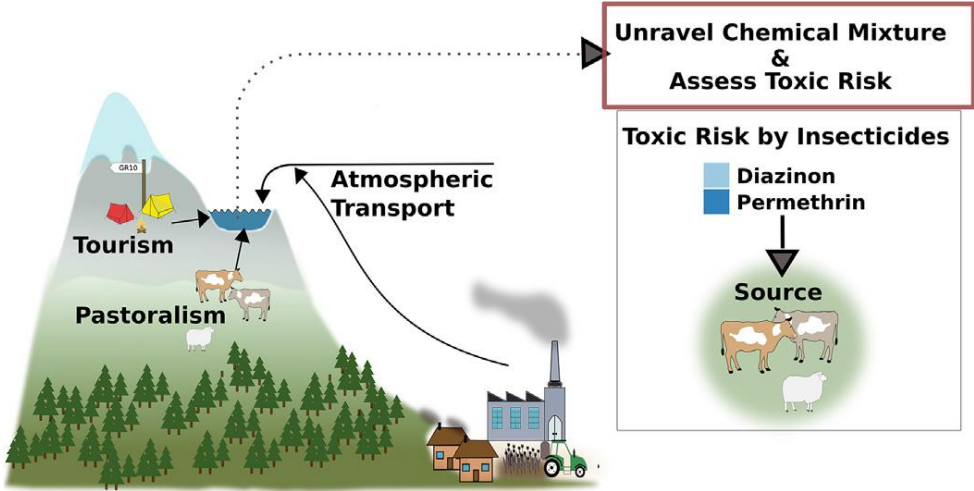
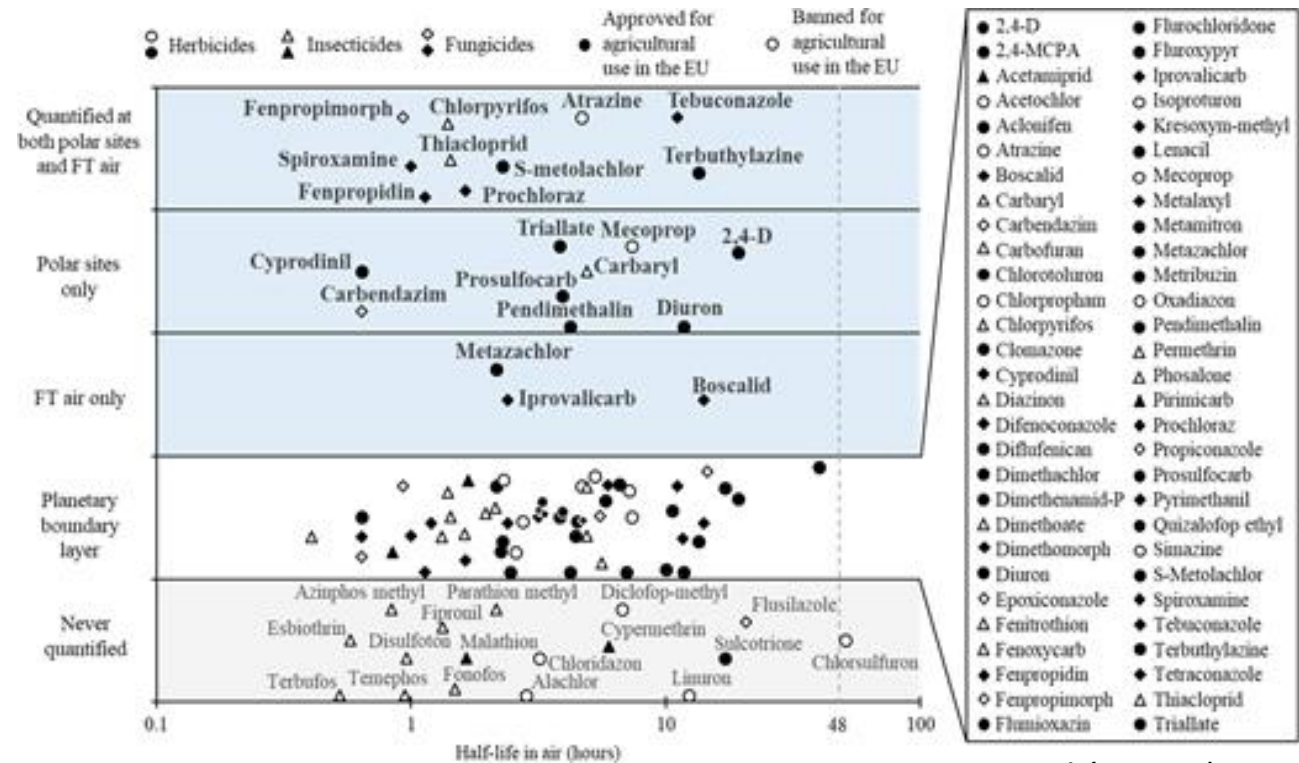
• <LD • <LQ • quantification

- Maximum concentrations up to 120 times higher than the concentrations monitored in background site

Context : evidence for long range transport for Current Used Pesticides

Contamination of rainwater, fog, but also recently in clouds
(Bianco et al., 2025) and mountain lakes (Machate et al., 2022)

Concentrations in gaseous and particulate phases

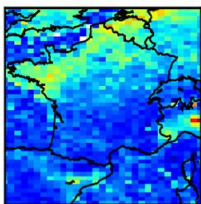


=> Source of exposure of natural ecosystems

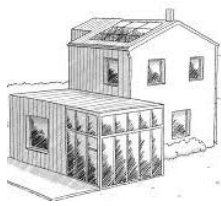
Outline



Agricultural practices



Environmental contamination



Human & ecosystem exposure



Effects

Recent studies

1- Modelling

- *in silico* approaches
- process-based modelling
- machine learning

2- Measurements

- emission by spraydrift, volatilization
- heterogeneous degradation, transformation products
- epidemiologic approaches
- toxicological effects through inhalation

3 – Mitigation techniques

Remaining challenges

1- Improve our knowledge

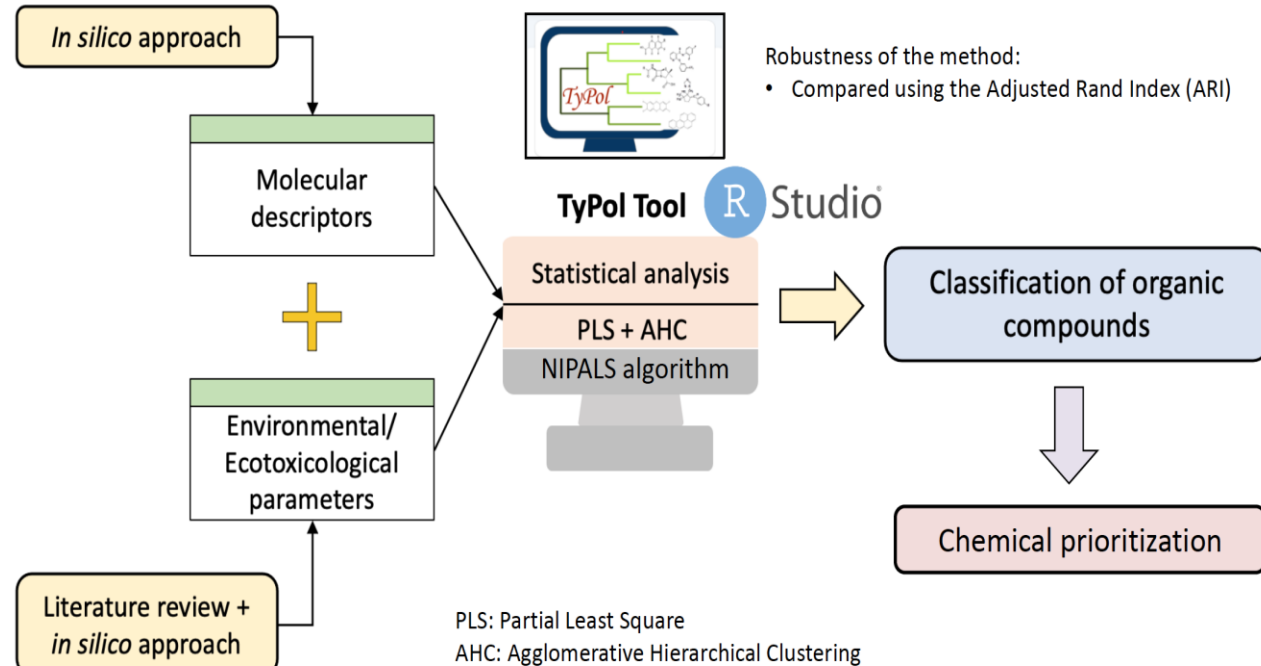
2- Implication for risk assessment

3- Interdisciplinarity

Recent studies based on *in silico* approach

***In silico* approach to classify compound fate or effect from their molecular properties**

Exemple: the TYPOL tool



Applied to predict 1) emission potential by volatilisation



- ⇒ Discriminate pesticide present or not in the atmosphere
- ⇒ Identify molecular descriptors for pesticides with a high potential of volatilization

From Servien et al. (2014)

2) molecular drivers of pesticide toxicity with a focus on the inhalation route

implement toxicological indicators: activation of xenobiotic receptors & oxidative stress & mitochondrial toxicity

Genard-Zielinski et al. (submitted)

Recent studies based on process-based approach (1/2)

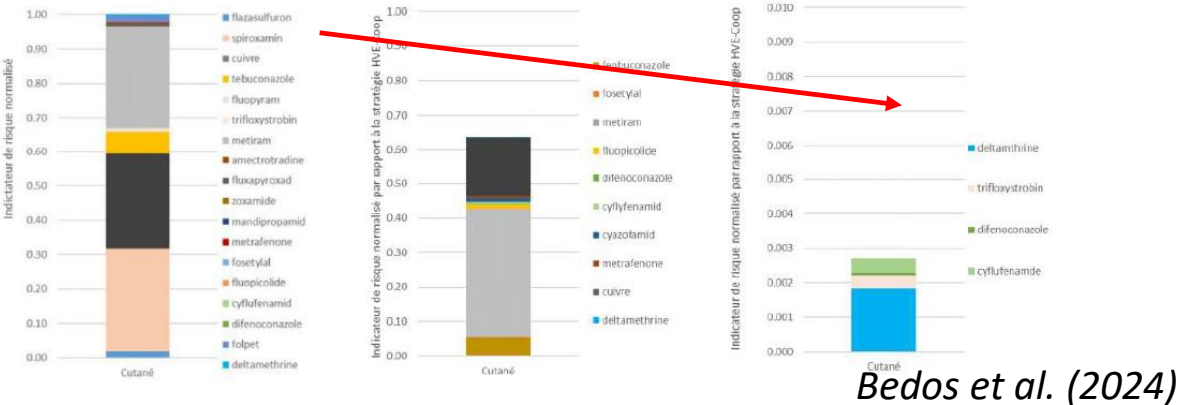
Modelling practices – exposure at different scales: local, landscape, regional/national

The case of bystander & resident exposure

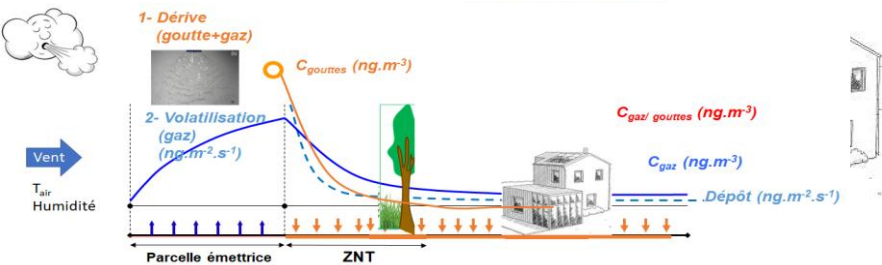
Prediction of the dermal exposure of bystanders by spraydrift

ADDISpraydrift model for vineyard application (*Djouhri et al., 2023*); different protection strategies; a risk indicator standardized by the cumulative indicator of the conventional strategy (based on the AOEL)

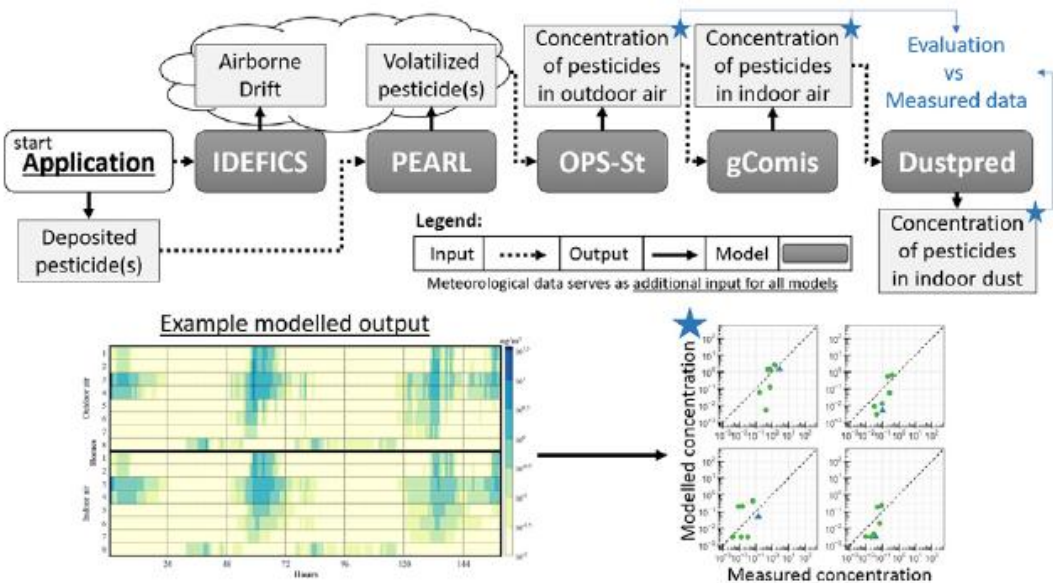
Conventionnal *0 CMR* *Resistent grape varieties*



- ⇒ Contribution of each substance
- ⇒ Efficacy of alternative strategies



Prediction of the resident exposure due to spraydrift, volatilization and indoor dust
the OBOmod model framework *Figueirido et al. (2022)*



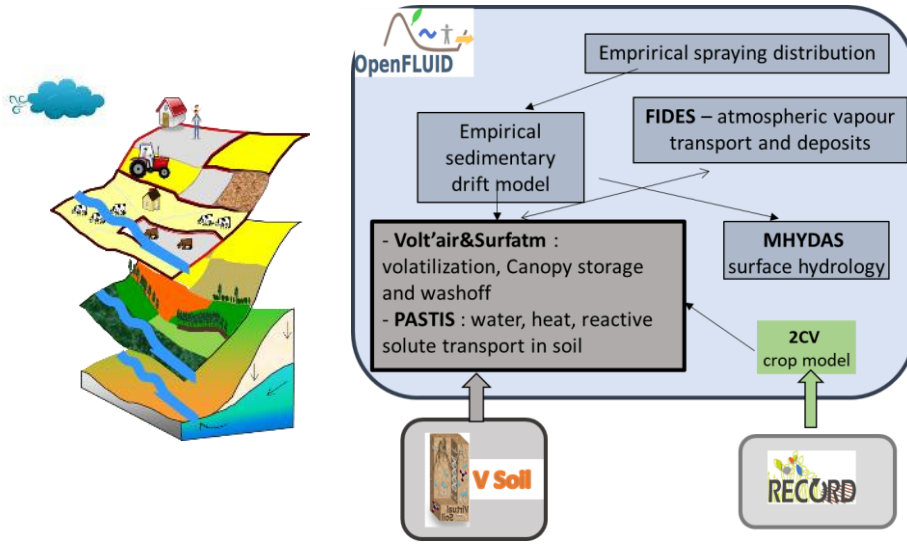
=> In addition to spray drift, volatilization & pesticides in house dust are important routes for residents' exposure

Recent studies based on process-based approach (2/2)

Modelling practices - exposure at different scales: local, landscape, regional/national

Landscapes: hydrological and atmospheric transfers

Exemple of the MIPP model (Voltz et al., 2019)



Examples of applications in vineyard considering intra-field heterogeneity – rows vs inter-rows:

- Fate at the plot scale (Dagès et al., 2024)
- Soil organism exposure after coupling with an individual based model (Devalloir et al., 2026)

=> **An effect of vineyard spatial structure on exposure dynamics**

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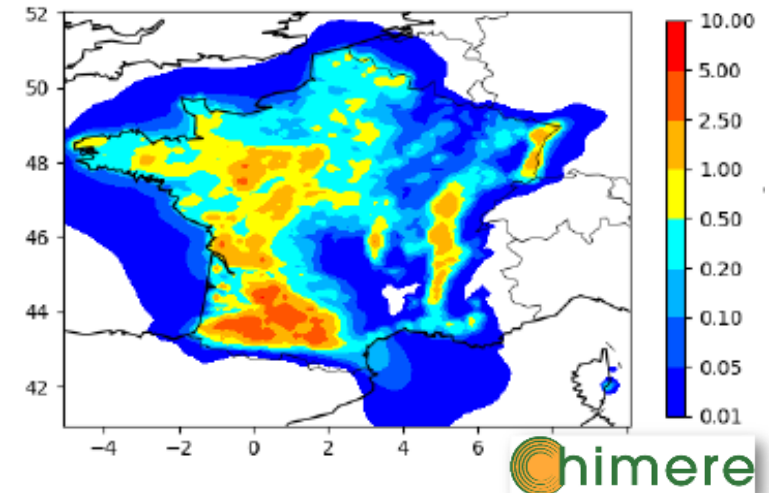
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Regional & national scales: atmospheric transfers & behaviour with an atmospheric chemical model

Exemple of the CHIMERE model (Couvidat et al., 2021)

S-metolachlor concentration (ng/m³) (volatilisation)



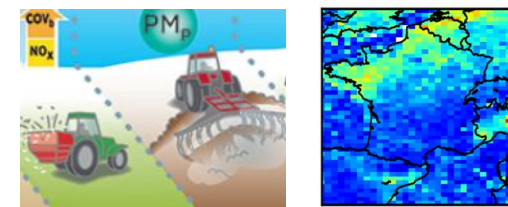
=> **A satisfactory agreement with monitoring data for the 2 substances studied (S-metolachlor, Folpel)**

=> Information on agricultural practices & dataset covering a longer period for volatilization fluxes would improve the prediction

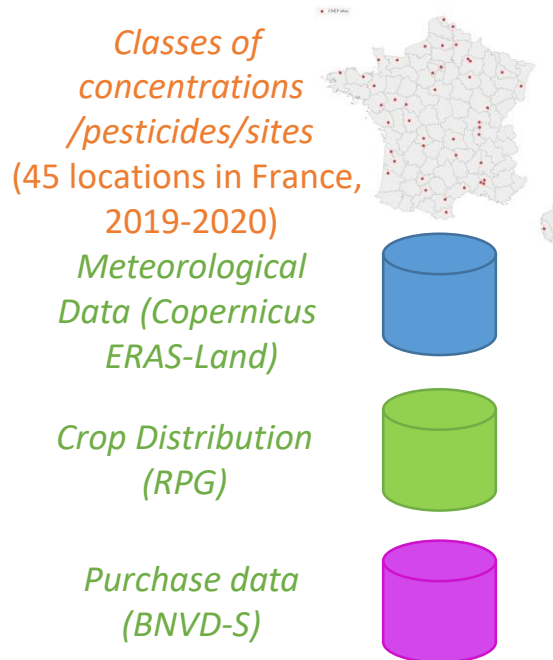
Recent studies based on Deep Learning approach

Spatio-temporal pesticide concentration modeling based on monitoring data of the atmospheric background contamination

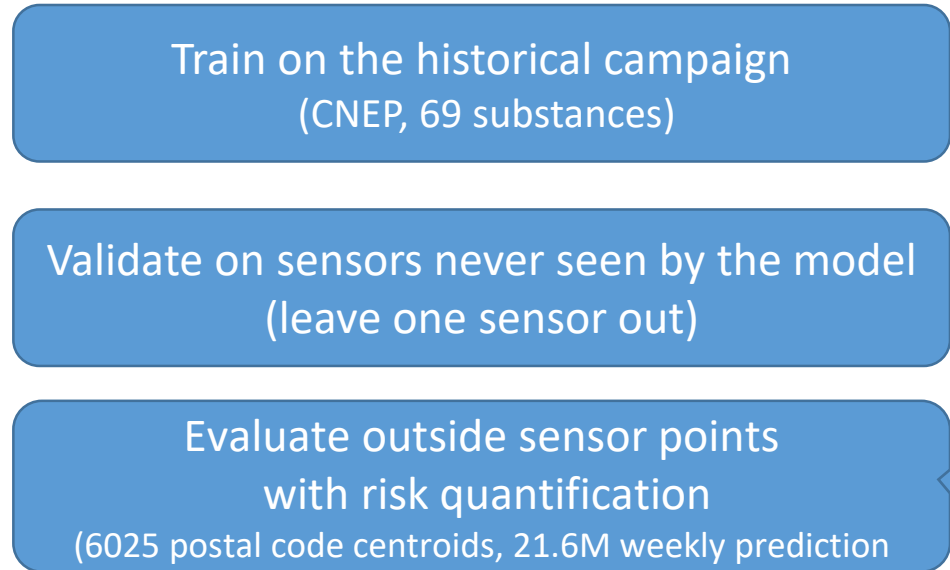
Method: Learn the link between **agricultural context** and **measured air concentration**, then evaluate the concentration at every postal code as a virtual sensor



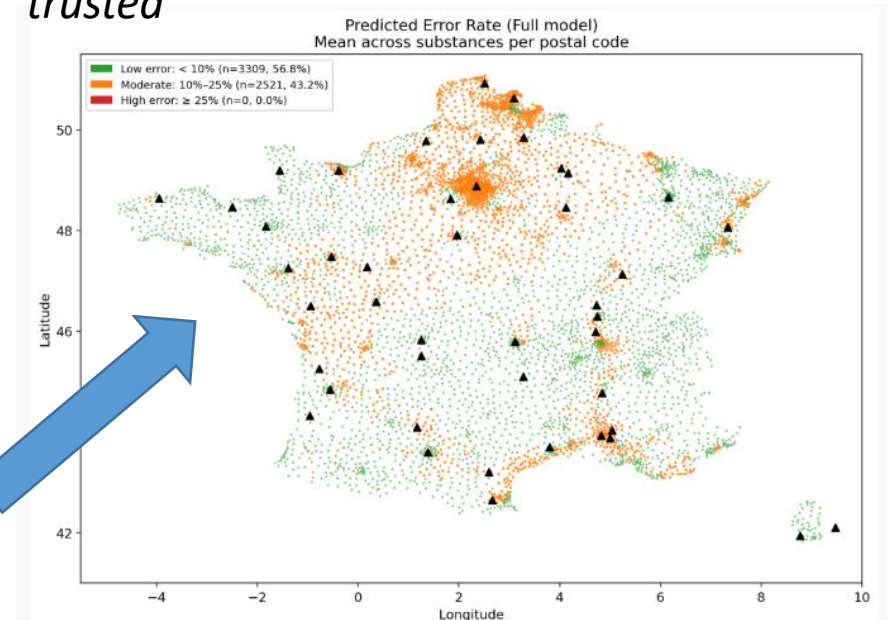
1- Model Inputs



2- Training, then evaluation at new locations



3- Predicted error risk at every postal code: where the estimator says it should not be trusted



Rousselot (2026)
Project Horapest

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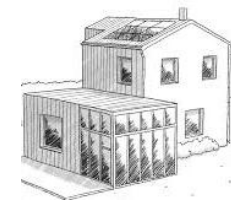
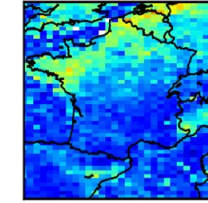
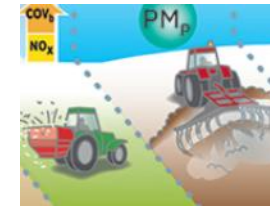
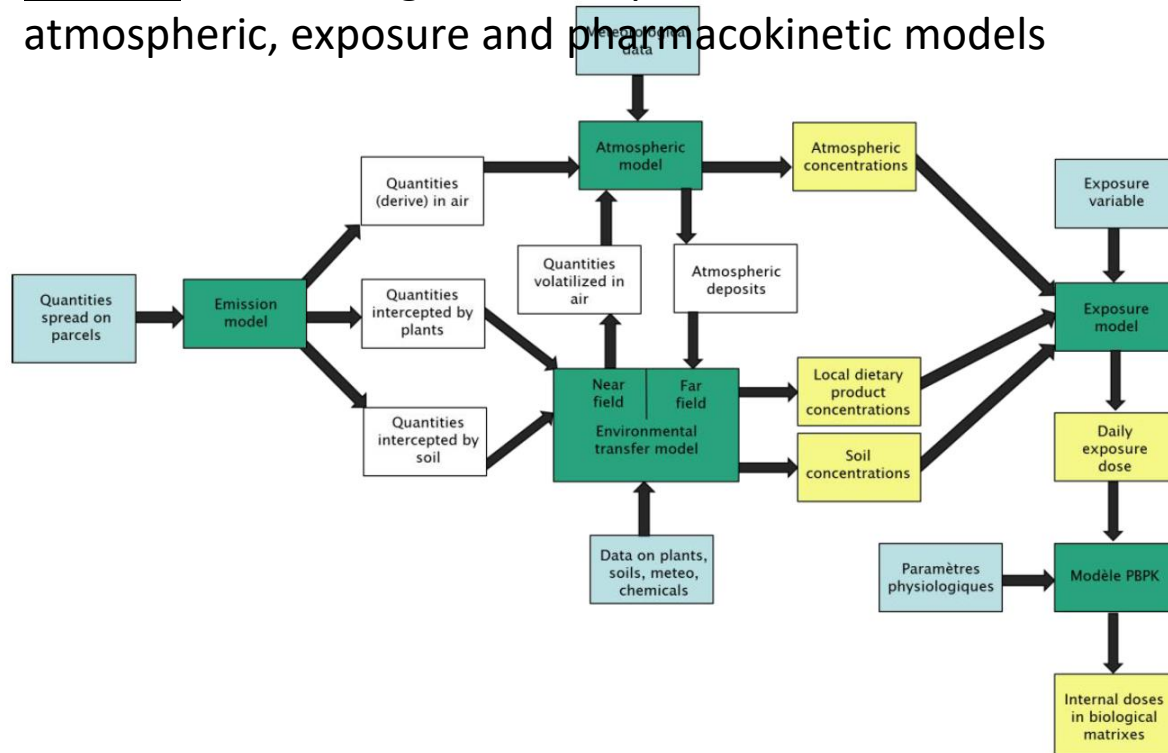
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Accuracy depends on choices made in building the inputs
Recommendation to develop hybrid approaches based on Physics informed neural networks (PINNS)

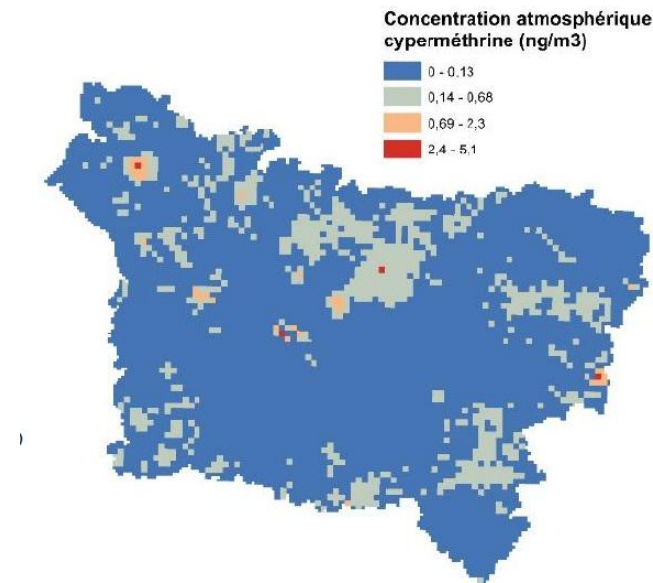
Moving towards an integrated approach up to internal exposure

As proposed *e.g.* by Caudeville (2026) to characterize the territorial exposome and identify the most exposed territories

Method: monitoring data, GIS, probabilistic methods, available atmospheric, exposure and pharmacokinetic models



Exemple of results : Average daily internal exposure dose (ng/kg/d) considering various exposure pathways for cypermethrin



Need to consider all relevant processes
With a challenge on interoperability of databases
Couple with toxicological studies

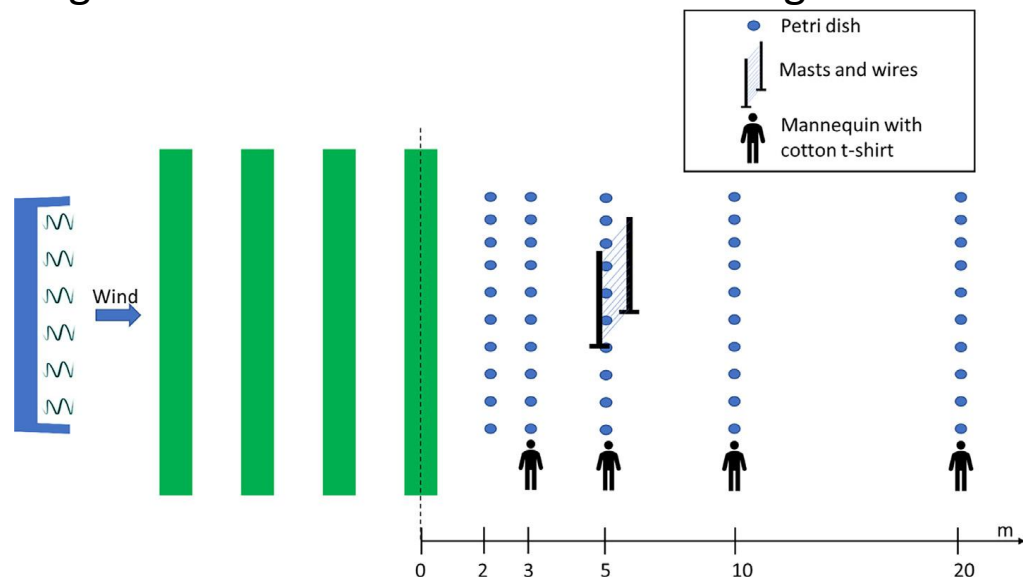
Recent studies on measuring emissions

Spray-drift

Protocols set up for **sedimentary drift**, **aerial drift** and **exposure of bystanders/residents**

(e.g. *Figueiredo et al., 2021*)

Estimate the efficacy of spray application techniques, hedges and their combination in reducing drift



An **unified protocol** (with tracers) for:

Vineyards: *Verges et al. (2024)*

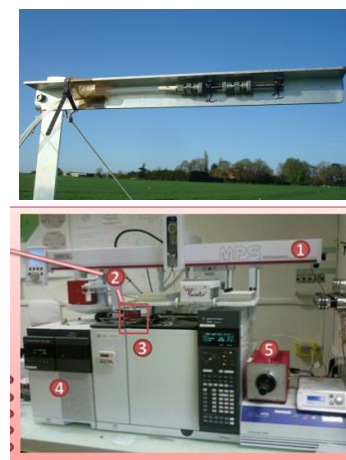
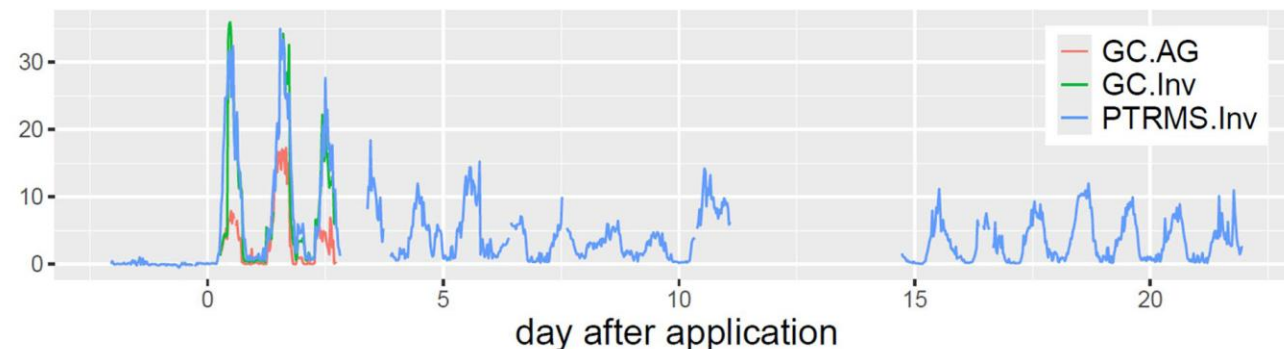
Orchards : *Hudebine et al. (2025)*

Arable crops: *Perriot et al. (2024)*

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Volatilization of chlorothalonil **up to 3 weeks after application** (ng/m²/s)

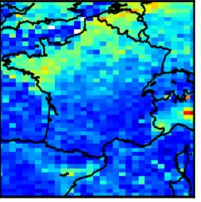


Active sampling with 1) Thermal desorption / GC / MS and 2) Proton Transfer Mass Spectrometer



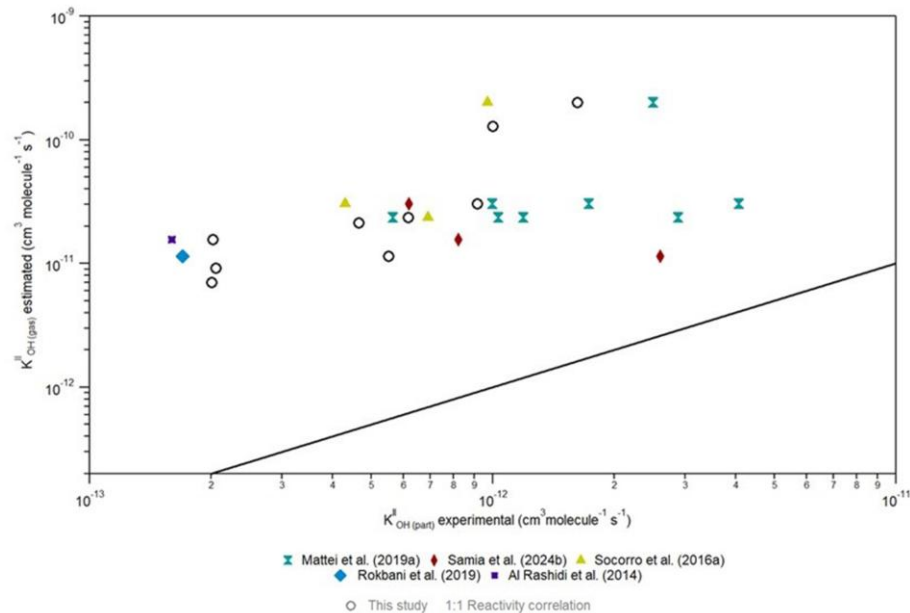
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Recent studies on measuring degradation, transformation products and gas/particle partition



Heterogenous degradation and Transformation products

Comparison of
AOPWIN gas-phase OH degradation rate constants
with experimental heterogeneous OH rate constants



=> reduced reactivity of pesticides adsorbed onto atmospheric particles; One hypothesis of observed LRT

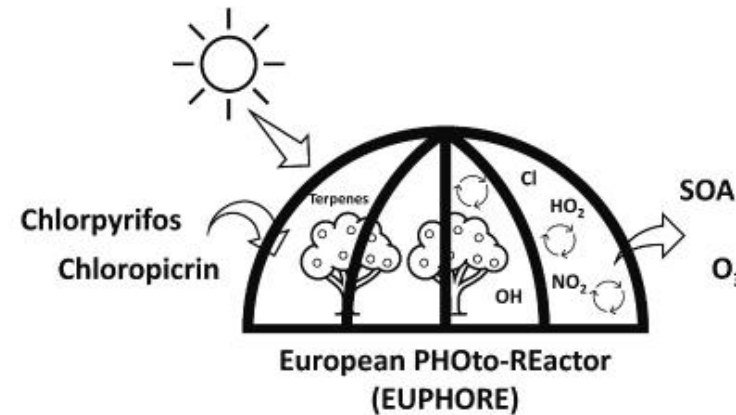
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Samia et al. (2026)

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Homogeneous degradation : The Euphore Chamber
Valencia, Munoz et al. (2023)



=> Ozone and secondary organic aerosol production

Gas/ particulate phase partition and pesticide distribution over the size distribution of atmospheric particles

Few observations (e.g. Degrendele et al., 2016; Mayer et al. 2024b; Samia et al., 2026)

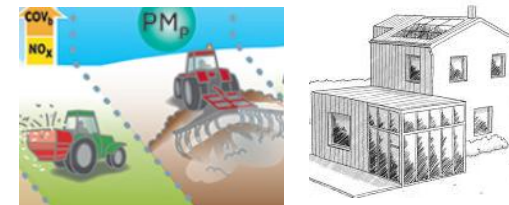
There is a need to collect data, as this is essential for predicting the fate of pesticides in the atmosphere and their impact on human and environmental exposure p. 14

Recent studies based on epidemiological approaches

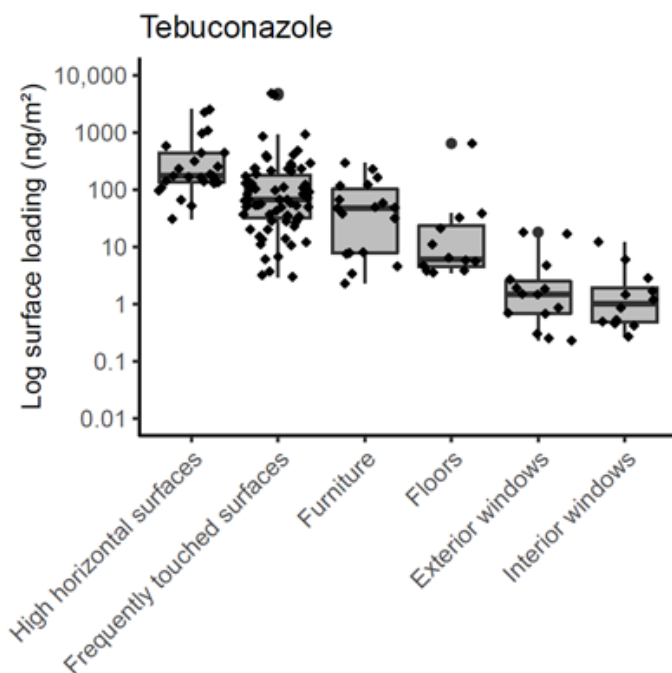
Assess the effect of the local environment, home characteristics and occupant behavior on residential contamination

Method:

- 8 compounds : benalaxyl, boscalid, cyflufenamide, cymoxanil, folpet, pyraclostrobin, tébuconazole, trifloxystrobine
- 3 + 28 homes in a vineyard region of France; wipe samples on various surfaces outside and inside during the spraying season
- Multilevel structural equation models

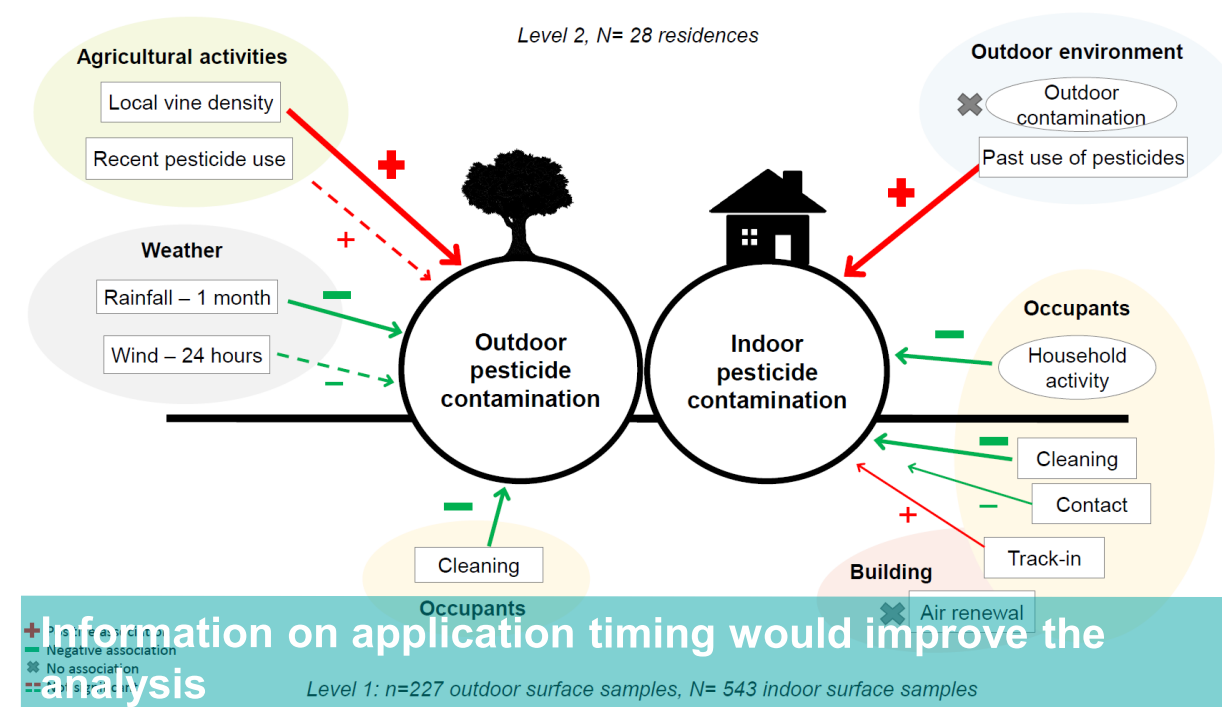


Level of contamination depends on the surface nature



(Teyssiere et al., 2023)

Key factors identified



Teyssiere et al. (2026)

Recent studies based on epidemiological approaches

Assess the association between prenatal residential exposure to pesticides and wheezing or asthma



POPULATION AND OUTCOMES



French nationwide cohort started in 2011

> 8 000 mother-child dyads

Wheezing: self reported by parent's children (2M-3.5Y)

Asthma: self reported according to ISAAC criteria (5.5Y & 10.5Y)

METHODOLOGY

PRENATAL EXPOSURE

Domestic use
Self-reported questionnaires for 8 prenatal uses

Agricultural pesticides (< 1,000 m around pregnant women's home)
34 pesticides estimated by geographical information system (GIS)



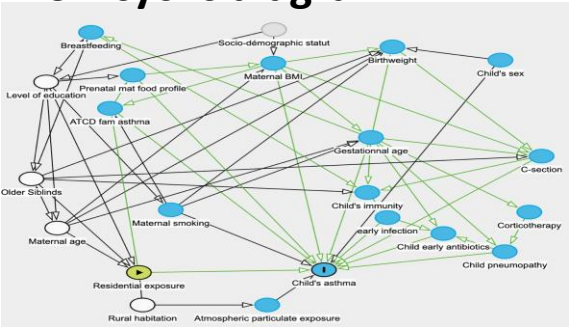
ANALYSES

Covariates : selection with **directed acyclic graph** and **multiple imputation** for missing data

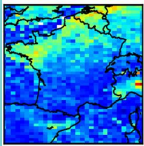
Logistic regression models
1/ **Monopollutant** model with selected **p-value ≤ 0,2**
2/ **Multipollutant** model **P- value ≤ 0,5**



Non-cyclic diagram



Challenge: replace the current proxy based on pesticide use with air concentration levels and the level of deposition on surfaces



These epidemiological results improve prevention

LOGISTIC REGRESSIONS

2/ Multipollutant model

Domestic use

Wheezing  **Asthma**

Anti-flea & tick
aOR = **1.22**
[1.02; 1.44]



Agricultural use

Wheezing  **Asthma**

Triadimenol
aOR = **1.23**
[1.09; 1.38]

Propyzamide
aOR = **0.70** [0.48; 0.92]
Pendimethalin
aOR = **1.37** [1.02; 1.73]
Triadimenol
aOR = **1.29** [1.07; 1.51]

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Recent studies in measuring toxicity

Toxicological approaches: *in vitro* experiments to assess

- 1) What are the mechanistic arguments in favour of a link between airborne pesticides and respiratory health?
- 2) The relevance of extrapolating toxicological reference values (TRVs) from the oral route to the inhalation route



Method:

- 4 compounds : boscalid, trifloxystrobin, pendiméthaline, tébuconazole
- 2 types of cells : human lung cells (BEAS-2b) and human liver cells (IHH)
- selected effect markers : activation of nuclear receptors, redox status, inflammation + lipid metabolism for liver cells
- Cell exposition for 24h to non toxic doses for each compound alone or as a mixture of 2 or 3 or 4 compounds

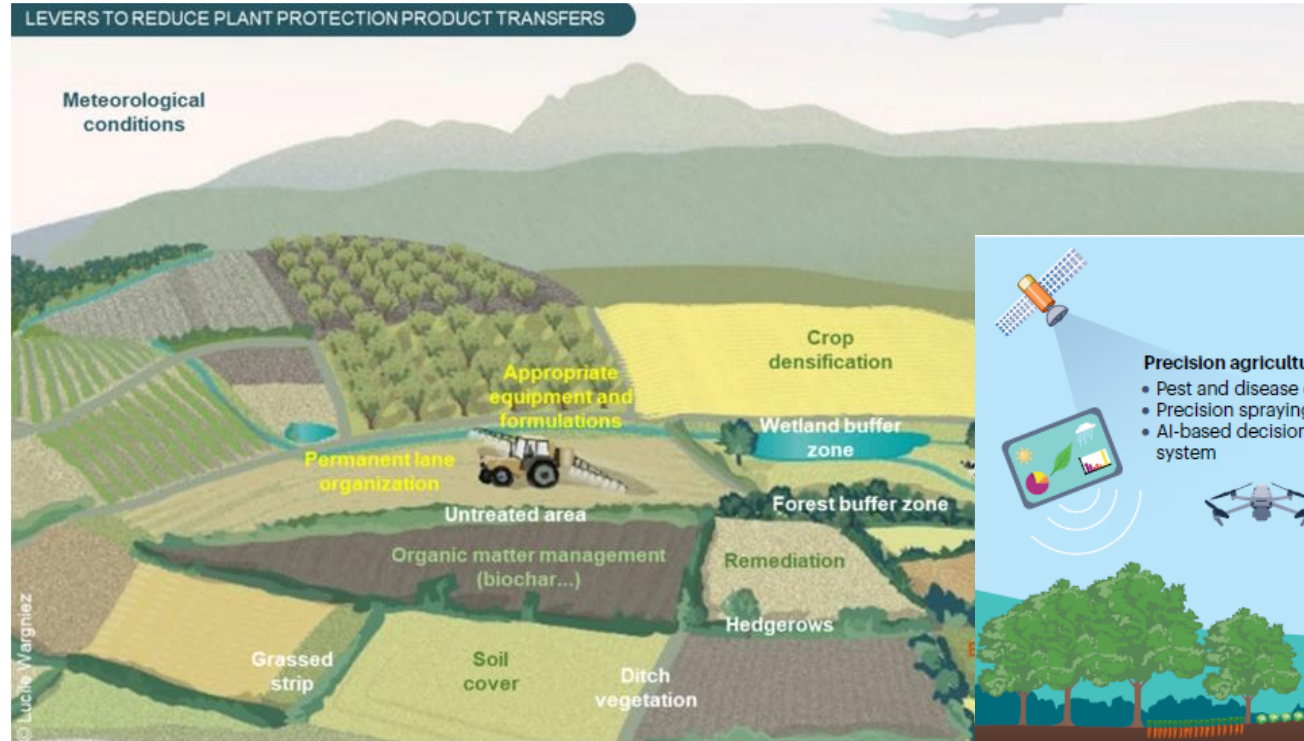
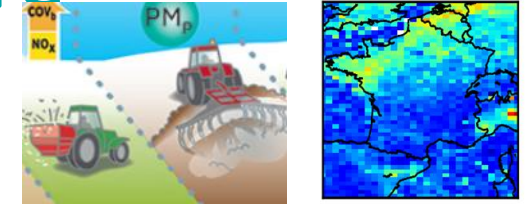
=> First results:

- **Viability:** both models are sensitive to the same doses of the four pesticides, either alone or in combination; trifloxystrobin is highly toxic (to both cell models).
- **Specificity of the effects:** the initiating and key molecular events are specific to each of the diseases studied, and the two models do not respond in the same way to the pesticides

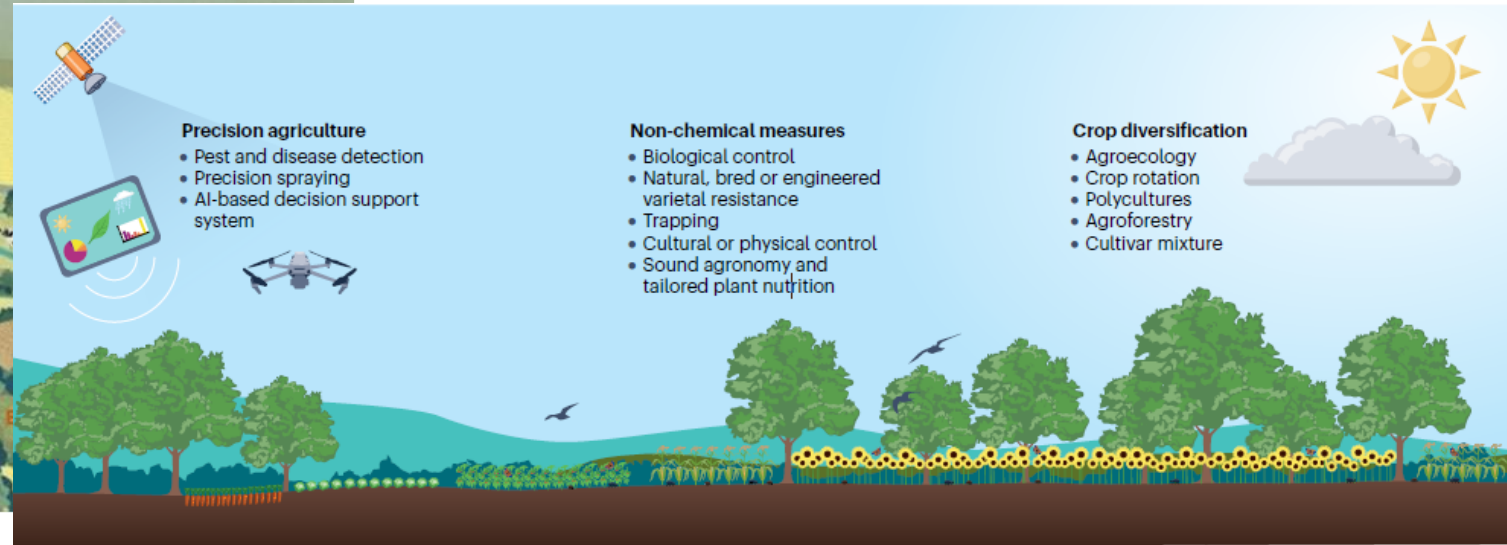
Need to go on with other compounds,
transformation products ...

Mitigation techniques to limit transfers and exposure

Levers to reduce pesticide transfer at the application, plot scale and landscape scales



Tournebize et al. (2025)



Target et al. (2025)

Combinations of levers are required but the efficacy of these combinations needs to be assessed
Fate of biopesticides needs to be further studied

Remaining Challenges: improve our knowledge on

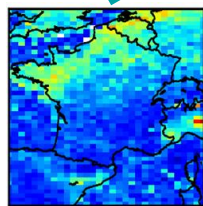
Mitigation levers & combination

- Agricultural practices
- Landscape organisation



Emission:

- Source of spray droplets
- Volatilization with time + formulation
 - New practices
- Quantify their contribution



Modelling

- Different scales
- Process based & deep learning
- Dataset for testing

Monitoring

- Targeted/untargeted analysis
- Active and passive sampling
- Trends over several years

Transformation products

Persistence

Gas/Particle partition and size distribution

Assessment of the contribution of each **pathway of exposure**: inhalation vs dermal vs ingestion



Vulnerable populations
Exposition periods

Assessment of the contribution of spraydrift droplets vs gaseous/particles

Past exposure
Epidemiological studies

Specific **reference toxicity value** for inhalation for relevant compounds (to be identified)

Mixture effect



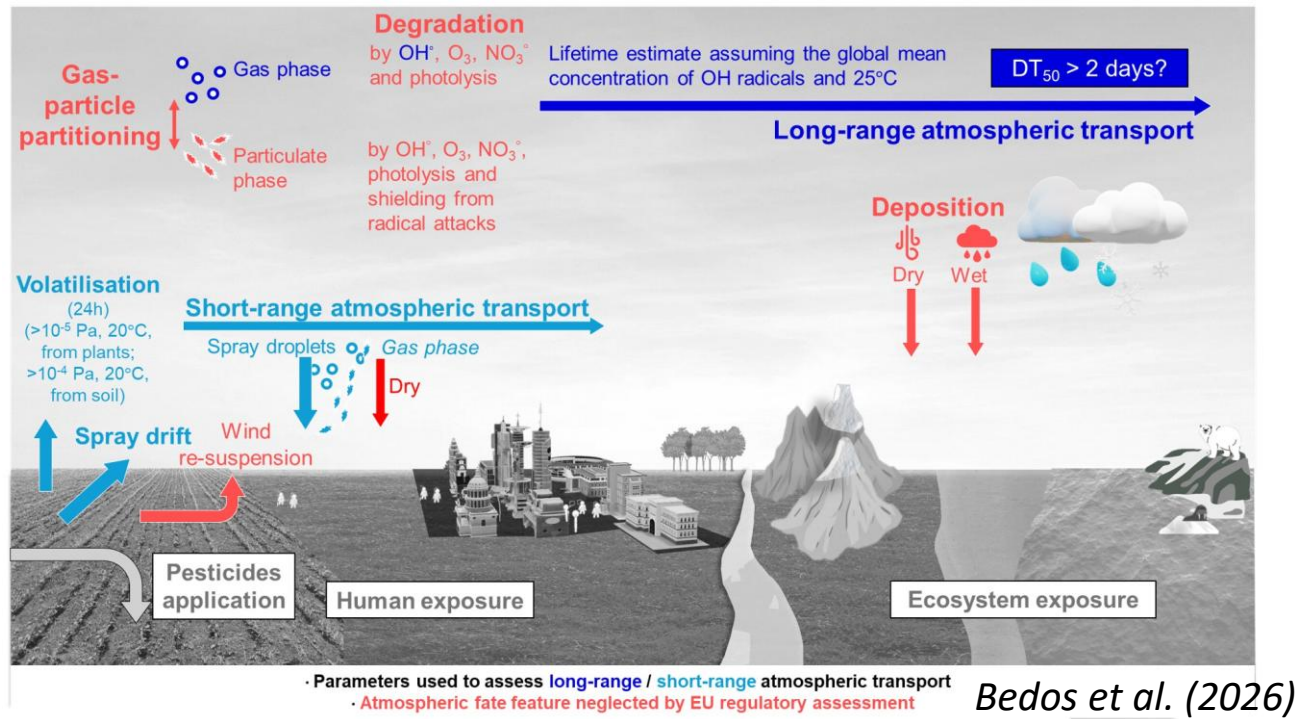
Multistress

Identify potential specific effect through inhalation & associated toxicological mechanisms
Toxicological studies

To be completed regarding ecotoxicology

Remaining Challenges: improve risk assessment ...

... in the « air chapter »



Main areas for improvment are identified
Among them:

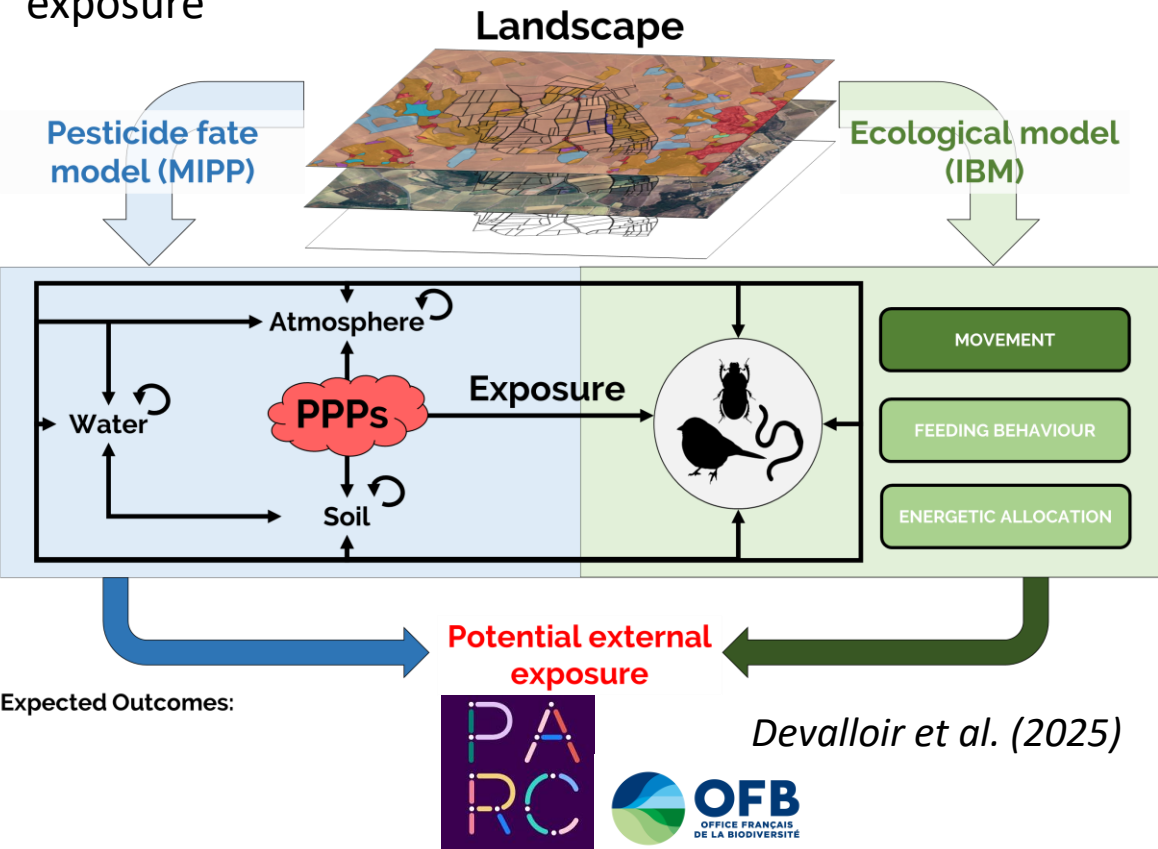
- Better estimate DT50Air
- Provide PECAir

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... essentially done per active substance and per treated field => a landscape approach required

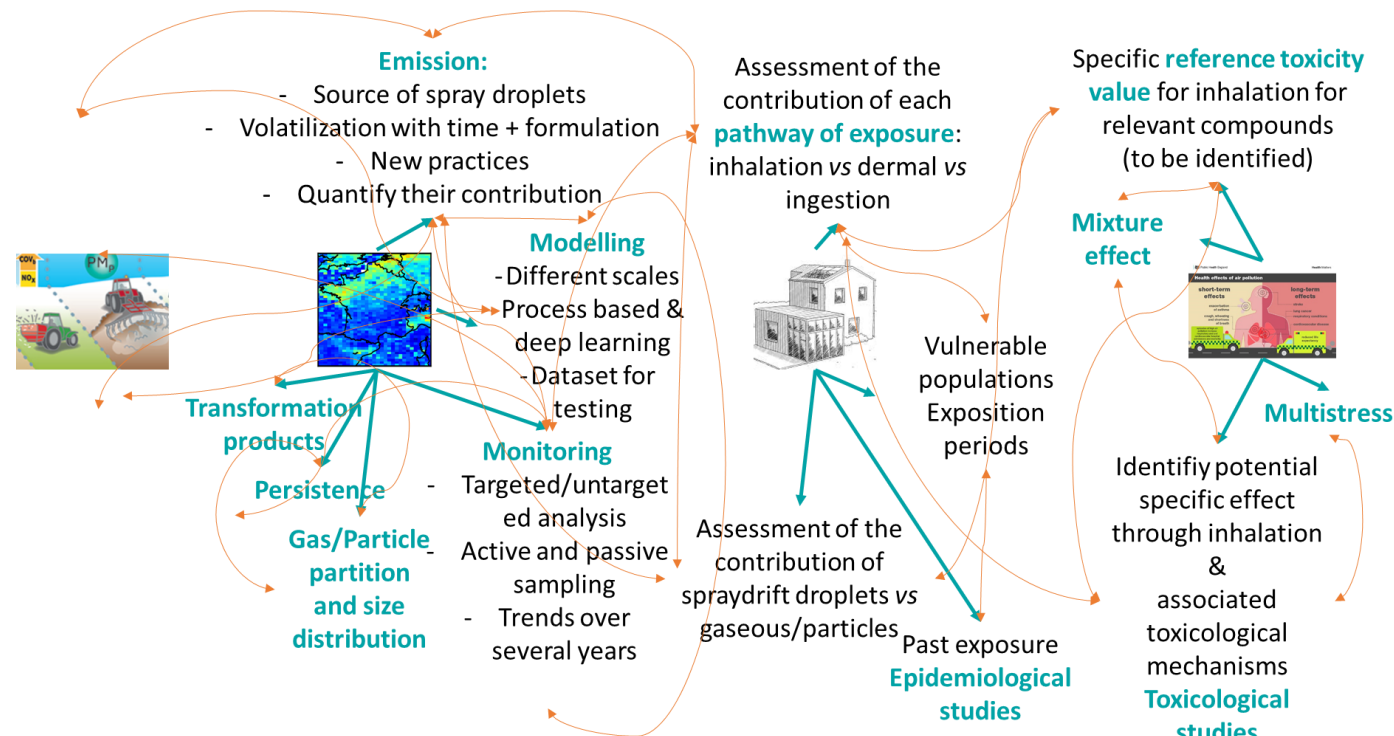
Tarazona et al. (2025)

Exemple: provide a landscape scenario of soil organism exposure



Remaining Challenges

- Integrated approach



In addition :

- the estimation of the different **uncertainties** in the chain *Agricultural practices – effects*
- Context of **climate change & One Health**

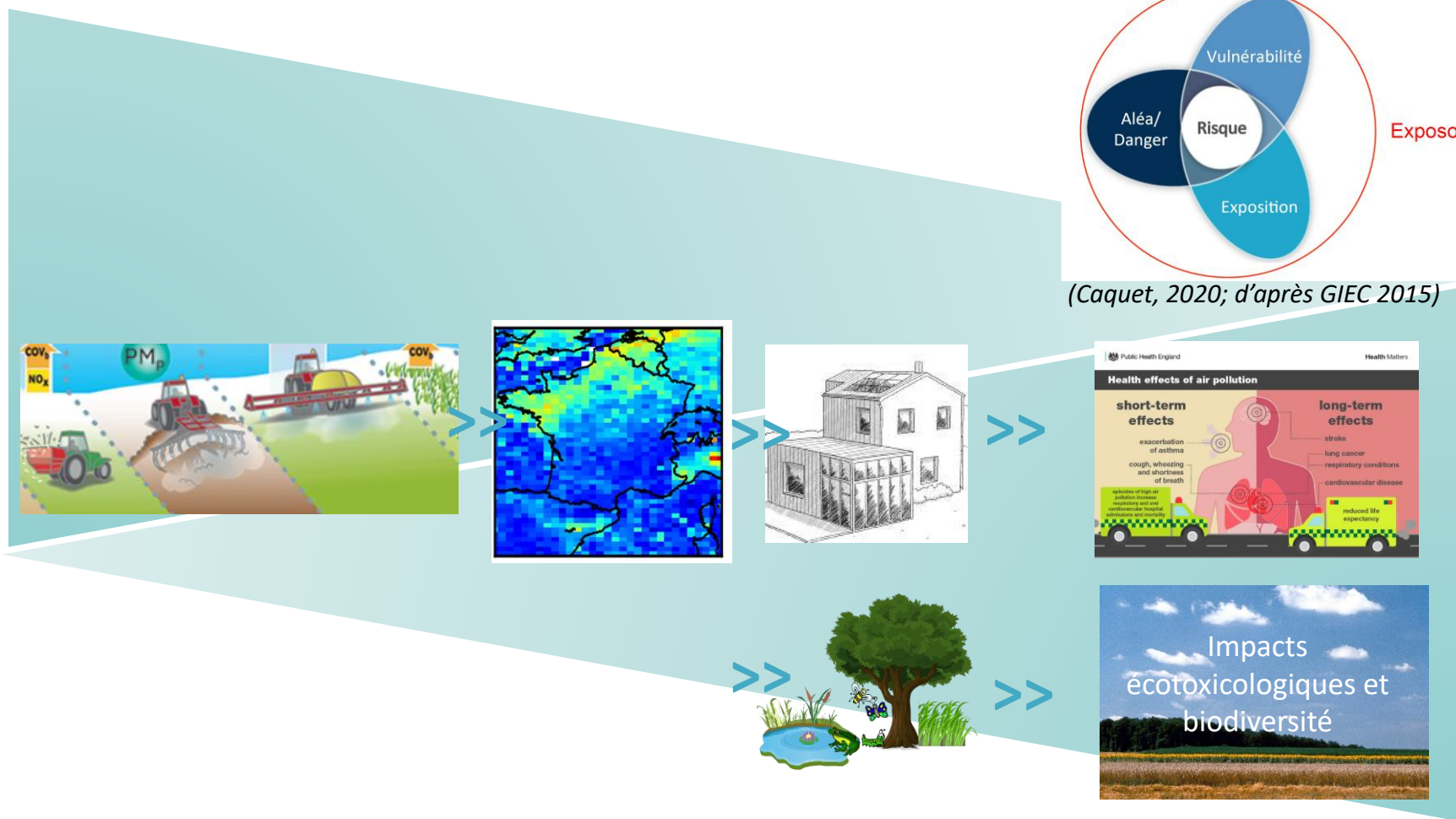
Remaining Challenges: The need for interdisciplinary approaches



towards interdisciplinary*
environmental and health
research for

- an integrative modelling of mechanisms linking agricultural practices and health effects
- global-scale models capable of estimating and predicting near-real-time pesticide exposure risks

* Environmental sciences
(physics, chemistry,
agronomy), epidemiology,
toxicology, sociology,
economics, ...



Thank you for your attention!!



INRAE

XVIII SYMPOSIUM ON PESTICIDE CHEMISTRY

04/09/26 C. Bedos

List of publications:

Bedos et al. 2024: Conference in Montpellier, available on request
Bedos et al., 2026: <https://doi.org/10.1016/j.jhazmat.2026.141769>
Caudeville, 2026. HDR report, available on request
Couvidat et al., 2021: <https://doi.org/10.1016/j.jhazmat.2021.127497>
Dages et al., 2024: conference in Piacenza, available on request
Degrendele et al., 2016 : <https://doi.org/10.5194/acp-16-1531-2016>.
Figueiredo et al., 2021: <https://www.researchprotocols.org/2021/4/e27883>
Figueiredo et al., 2022: <http://dx.doi.org/10.1016/j.scitotenv.2022.153798>
Hubebine et al., (2025): <https://doi.org/10.1016/j.dib.2025.112202>
Loubet et al., 2025 : <https://doi.org/10.1038/s41598-025-13898-0>
Lcsqa, 2024: <https://www.atmo-france.org/actualite/pesticides-dans-lair-publication-du-premier-bilan-du-suivi-national>
Mamy et al., 2021: <https://doi.org/10.1016/j.jhazmat.2021.125613>
Margoum et al., 2025: <https://doi.org/10.1007/s11356-024-34945-9>
Mayer et al., 2024b: <https://doi.org/10.1016/j.atmosenv.2024.120680>
Mayer et al., 2024a: <https://doi.org/10.1021/acs.est.3c08488>
Pestiriv: <https://www.anses.fr/en/content/pestiriv-study-exposure-pesticides-people-living-wine-growing-areas>
Perriot et al., 2024: <https://doi.org/10.1016/j.dib.2024.110366>
Pesce et al., 2025: <https://doi.org/10.1007/s11356-023-26952-z>
Rousselot, 2026. PhD thesis. <https://theses.hal.science/tel-05653218>
Samia et al., 2026: <https://doi.org/10.1016/j.aeaoa.2026.100465>
Servien et al., 2014: <http://dx.doi.org/10.1016/j.chemosphere.2014.05.020>
Tang et al., 2025: <https://doi.org/10.1038/s43017-025-00673-y>
Tarazona et al., 2025: <https://doi.org/10.1016/j.envint.2024.108999>
Teyssiere et al., 2023: <https://doi.org/10.3390/ijerph20053882>
Teyssiere et al., 2026: https://www.nature.com/articles/s41370-026-00907-1.epdf?sharing_token=U1xTv1l2EvBXeKX3rWGbF9RgN0jAjWel9jnR3ZoTv0N22WuJ9N2YT7Y6zwwPsiENIEGdQdLz3tn3wn_5omVSFIrf2t_07FqoaLdcklabhxisKlu1TdReBzjeMQgahsCgDEKmjllboLJGes1Z4DPFYgfgDO076LTALrOuk5yE0yY%3D
Tournebize et al, 2025: <https://doi.org/10.1007/s11356-024-35496-9>
Verges et al., 2024: <https://doi.org/10.1016/j.dib.2024.110819>
Voltz et al., 2019: Fresenius conference, available on request