Decision support systems halve fungicide use compared to calendar-based strategies without increasing disease risk

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Journée APPLIBUGS

10 décembre 2021

WHERE TO FIND OUR WORK

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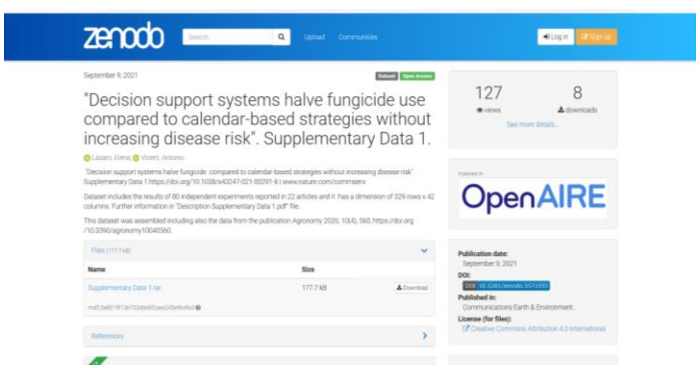
Abstract

The European Green Deal aims to reduce the use of chemical pesticides by half by 2030. Decision support systems are tools to help farmers schedule fungicide spraying based on disease risk and can reduce fungicide application frequency and overall use. However, the potential benefit of decision support systems compared to traditional calendar-based strategies has not yet been rigorously quantified. Here we synthesise 80 experiments and

https://www.nature.com/articles/s43247-021-00291-8

https://www.nature.com/articles/s41559-020-1109-6



https://doi.org/10.5281/zenodo.5571593

https://doi.org/10.5281/zenodo.5571614

BACKGROUND OF THE WORK

Why the interest in 1) halving the use of fungicides and 2) Decision support systems?

A set of policy initiatives by the European Commission with the overarching aim of making Europe climate neutral in 2050

The use of pesticides in agriculture contributes to pollution of soil, water and air. The Commission will take actions to:

- ✓ **reduce by 50%** the use and risk of chemical pesticides by 2030.
- ✓ **reduce by 50%** the use of more hazardous pesticides by 2030.

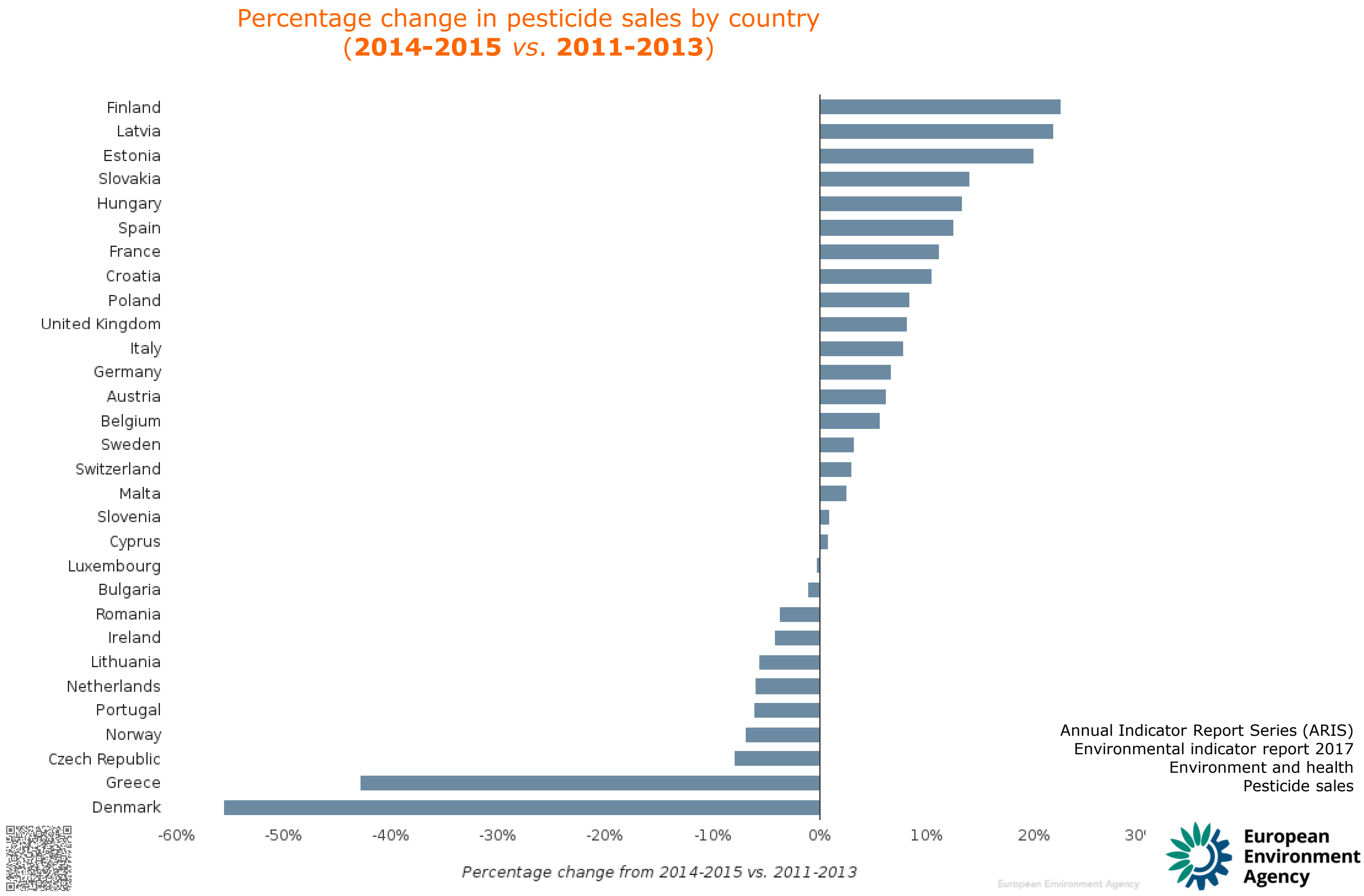
The **excess of nutrients** in the environment is a major source of air, soil and water pollution, negatively impacting biodiversity and climate. The Commission will act to:

- ✓ **reduce nutrient losses by at least 50%**, while ensuring no deterioration on soil fertility.
- ✓ **reduce fertilizer use by at least 20%** by 2030.

Antimicrobial resistance linked to the use of antimicrobials in animal and human health leads to an estimated 33,000 human deaths in the EU each year. The Commission will **reduce by 50% the sales of antimicrobials for farmed animals and in aquaculture by 2030**.

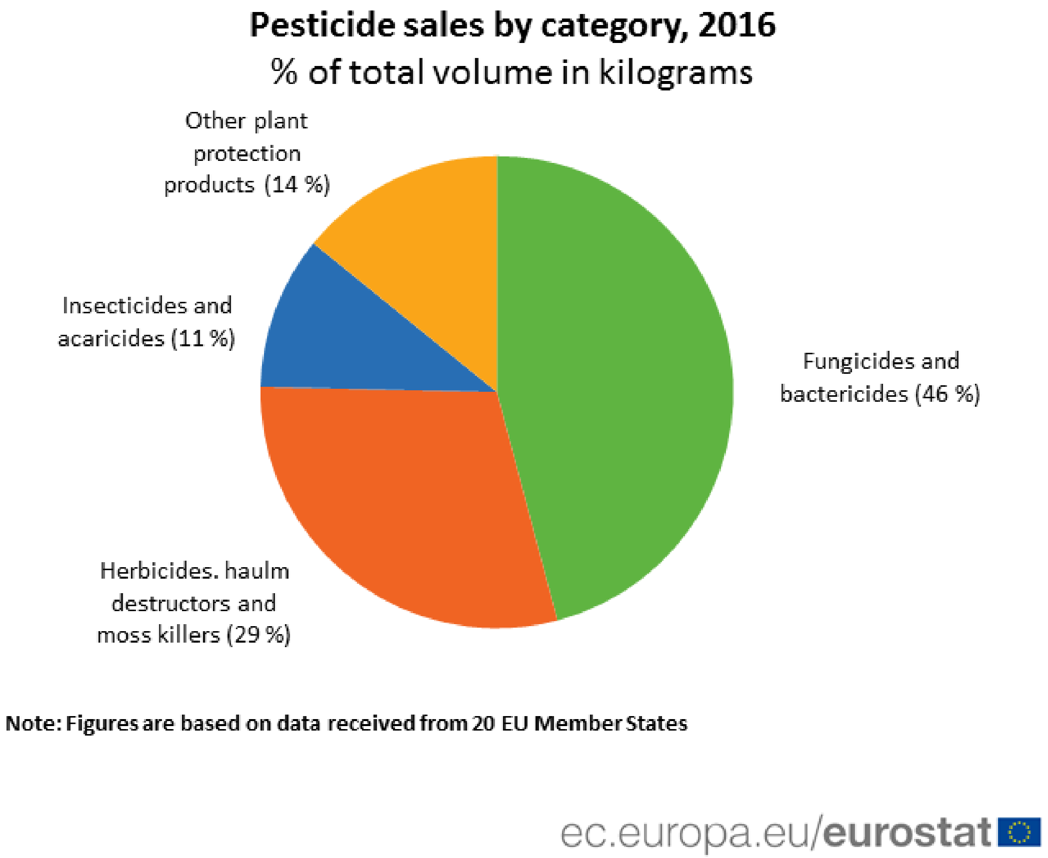
Organic farming is an environmentally-friendly practice that needs to be further developed. The Commission will boost the development of EU organic farming area with the aim to achieve **25% of total farmland under organic farming by 2030**.

❑ Use of pesticides in the EU

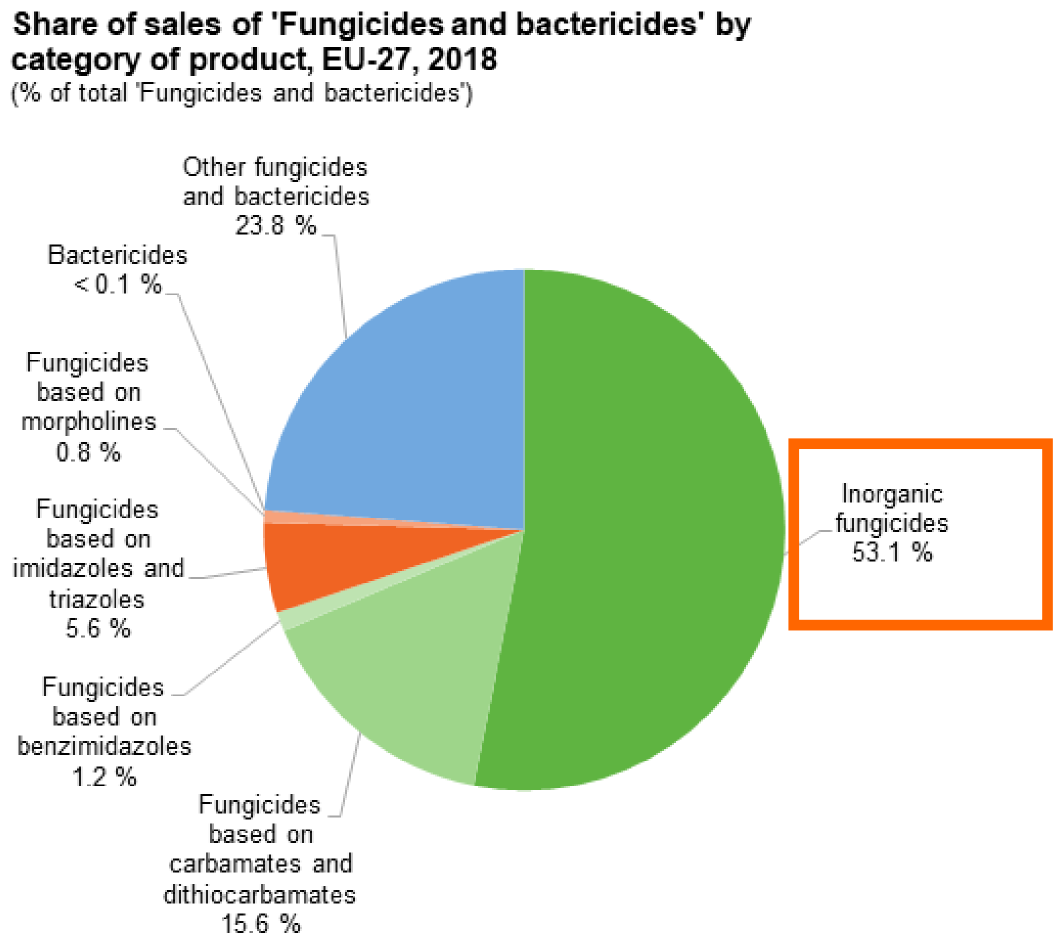


❑ Pesticide sales by major groups

UE, 2016

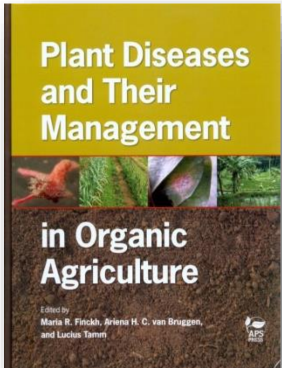


❑ Fungicide sales by category of product, EU



Note: This figure does not take into account confidential values.
Note: Reference year 2017 data used as 2018 for Denmark.
Source: Eurostat (online data code: aei_fm_salpest09)

❑ Fungicide use in organic farming



*"Control of **airborne diseases** by means of direct plant protection is **clearly more demanding in organic farming** systems because the plant protection products allowed are often less effective"*

Sustainability of three apple production systems

John P. Reganold*, Jerry D. Glover*, Preston K. Andrews† & Herbert R. Hinman‡

NATURE | VOL 410 | 19 APRIL 2001 | www.nature.com

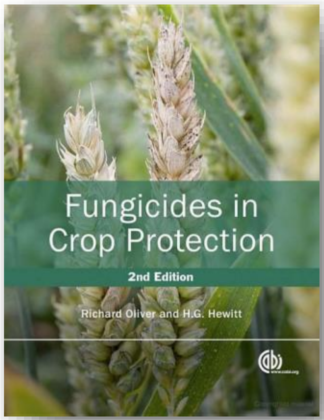
Table 3 Cumulative energy assessment

	Organic	Conventional	Integrated
Labour (h ha^{-1})	2,921	2,008	2,147
Labour (MJ ha^{-1})	2,337	1,607	1,718
Machinery (MJ ha^{-1})	73,974	73,560	73,560
Fuel (MJ ha^{-1})	173,400	182,919	182,919
Electricity (MJ ha^{-1})	10,794	10,794	10,794
Fertilizer (MJ ha^{-1})	311*	16,255	8,901*
Insecticide (MJ ha^{-1})	22,159	42,313	40,375
Fungicide (MJ ha^{-1})	18,023	12,922	12,855
Weed control (MJ ha^{-1})	141	31,931	13,350
Infrastructure (MJ ha^{-1})	144,188	144,188	144,188
Total input (MJ ha^{-1})	445,328	516,489	488,661
Total output (MJ ha^{-1})	526,544	570,745	550,076
Output/input (MJ MJ^{-1})	1.18	1.11	1.13

❑ Fungicide importance

Table 1.2. Breakdown of losses to disease and gains to genetic, cultural and chemical disease control in selected grain crop diseases in Australia; all figures are in AUS$ million. The 'potential loss' is the loss incurred if no control measures were in place; the 'actual loss' is the current estimate. The difference between potential and actual is assigned to either genetic control, cultural practices or fungicide control. It is clear even in low-input, sustainable agriculture situations like Australia that fungicides contribute heavily to disease control. (From Murray and Brennan, 2009, 2010.)

Disease	Potential loss	Actual loss	Genetic control	Cultural control	Fungicide control
Tan spot	676	212	200	155	108
Stripe rust	868	127	431	78	359
Septoria nodorum	230	108	36	51	35
Barley mildew	103	39	10	3	52



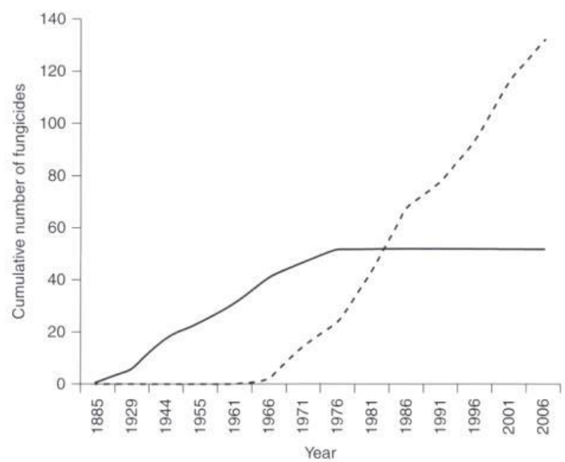


Fig. 3.2. Development of non-systemic (——) and systemic (– – –) fungicides.

- Towards low-fungicide-input disease management
  - Integrated Disease Management
    - Compulsory for conventional agriculture in the EU

      (Directive 2009/128/EC)

      Decision Support Systems (DSSs)

24.11.2009 EN Official Journal of the European Union L 309/71

DIRECTIVES

DIRECTIVE 2009/128/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL
of 21 October 2009
establishing a framework for Community action to achieve the sustainable use of pesticides
(Text with EEA relevance)

1. **Cultural practices**
2. **Monitoring, forecasting and warning systems**
3. **Decision based on thresholds**
4. **Non-chemical methods preferred**
5. **Pesticides with the least side effects**
6. **Reduced application frequency**
7. **Anti-resistance strategies**

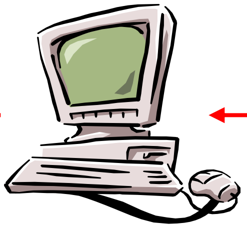
❑ DSS scheme

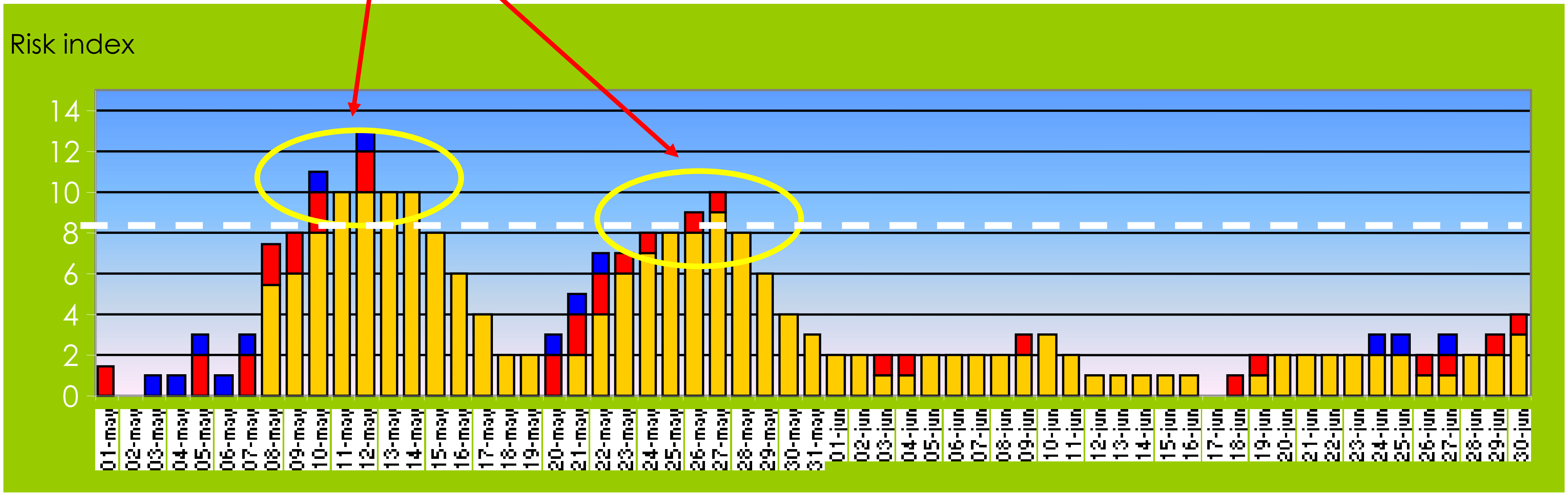
APPLICATIONS ACCORDING TO CRITICAL PERIODS OF INFECTION

WARNING STATION

Development and model validation

MONITORING ENVIRONMENTAL CONDITIONS





❑ Calendar vs DSS strategies

Evaluation of BSPcast Disease Warning System in Reduced Fungicide Use Programs for Management of Brown Spot of Pear

I. Llorente, Associate Professor, Institute of Food and Agricultural Technology-CeRTA, University of Girona, 17071 Girona (Spain); **P. Vilardell,** Research Agronomist, Mas Badia Agricultural Experiment Station, La Tallada, Girona (Spain); **R. Bugiani,** Research Agronomist, Servizio Fitosanitario-Regione Emilia-Romagna, Via di Corticella 133, Bologna (Italy); **I. Gherardi,** Associate Professor, Dipartimento de Produzione e Valorizacione Agraria, University Degli Studi di Bologna, Via Filippo Re 8, 40126 Bologna (Italy); and **E. Montesinos,** Professor, Institute of Food and Agricultural Technology-CeRTA, University of Girona, 17071 Girona (Spain)

Table 2. Incidence of brown spot on fruits at harvest in relation to timing and number of fungicide applications for each trial according to the treatment schedule used

Trial	Trtmt[x] schedule	Weeks after April 21																							no. of sprays	Fruit disease incidence at harvest (%)
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22		
1	Nontreated		-[y]	-	-	-	-	-	-	-	-		-	-		-	-								---	52.5
	Fixed	X		X		X	X	X		X	X		X	X		X	X								11	3.1
	CR 0.4	X		X		-	X	X		-	X		X	X		-	X								8	5.4 ns[z]
	CR 0.6	X		X		-	-	-		-	-		X	-		-	-								3	4.7 ns

[x] Fixed, commercial fungicide spray schedule applied at a fixed interval of 7 or 14 days depending on fungicide; CR 0.4, CR 0.5, or CR 0.6, fungicide sprays according to the BSPcast model predictions using 3-day cumulative daily infection risk (CR) action thresholds of 0.4, 0.5, or 0.6.

[y] X, sprayed once during this week; -, not sprayed; *, sprayed twice; **, sprayed three times after more than 20 mm rainfall following the fungicide application.

[z] Significance according to ANOVA with contrasts comparing fixed and BSPcast scheduled fungicide sprays; ns, not significant ($P > 0.05$); s, significant ($P < 0.05$). The P value for which F was significant is shown in parentheses.

OUR WORK

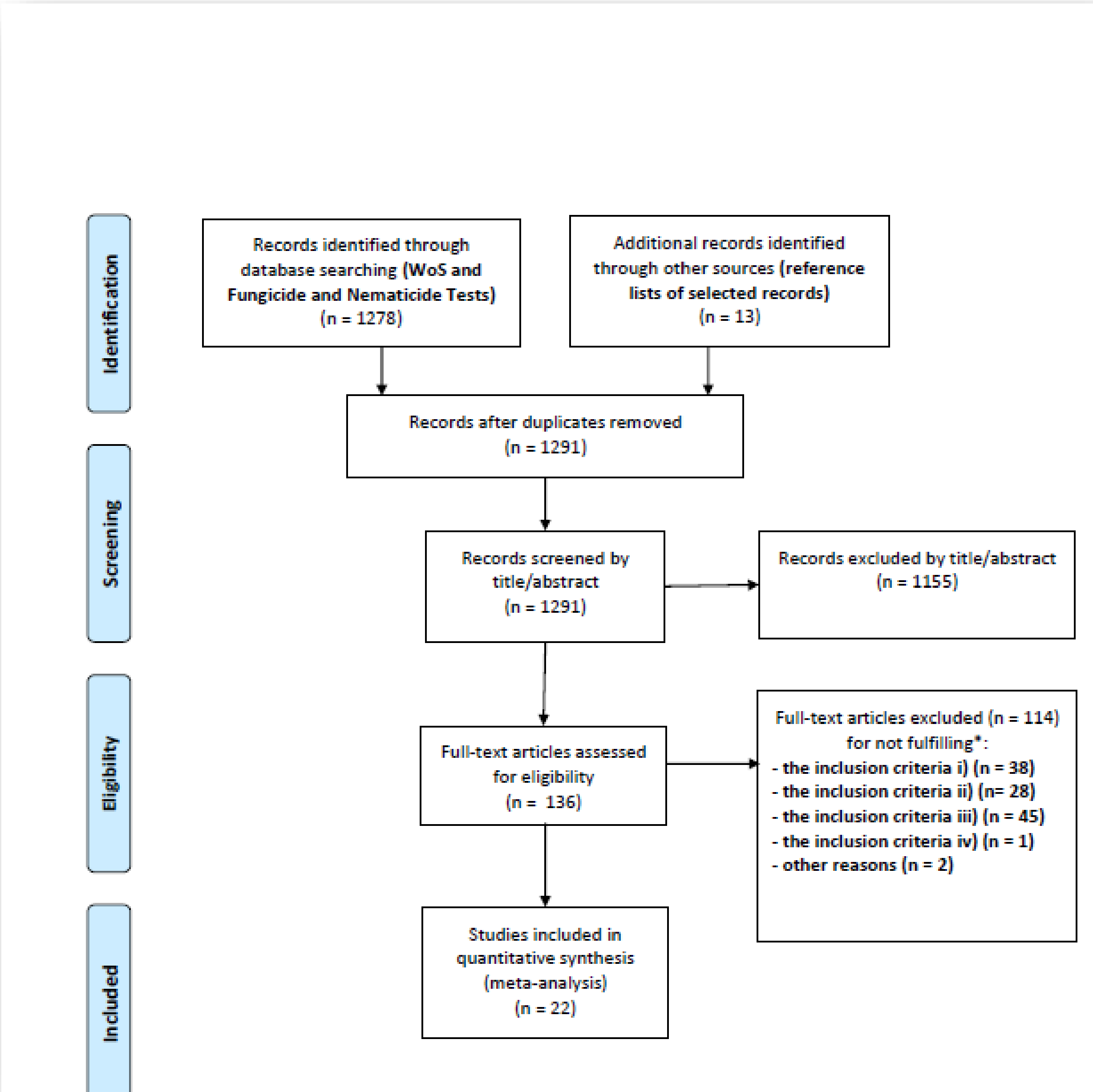
Try to answer wheter or not…

<u>Thanks to DSS</u>, reducing the use of pesticides (fungicides) by 50% is an achievable goal of the European Green DeaL

SYSTEMATIC REVIEW AND META-ANALYSIS

METHODS

DATA COLLECTION-SYSTEMATIC REVIEW



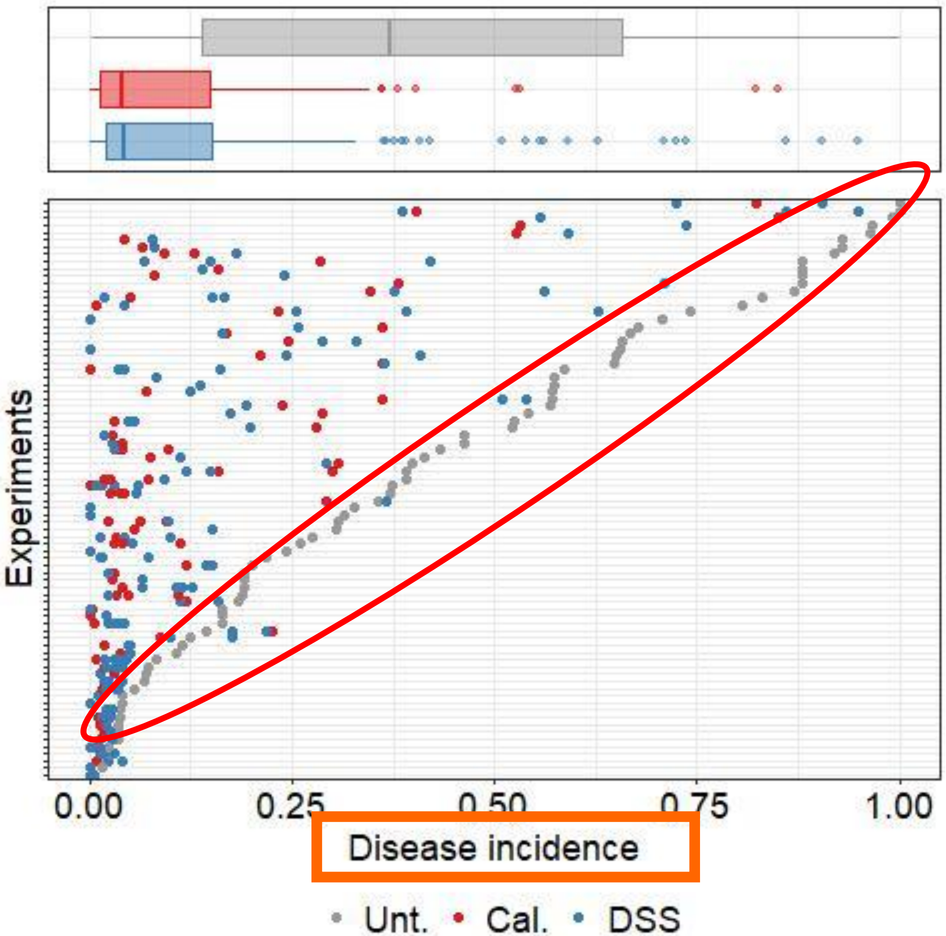
❑ **FINAL DATABASE**:

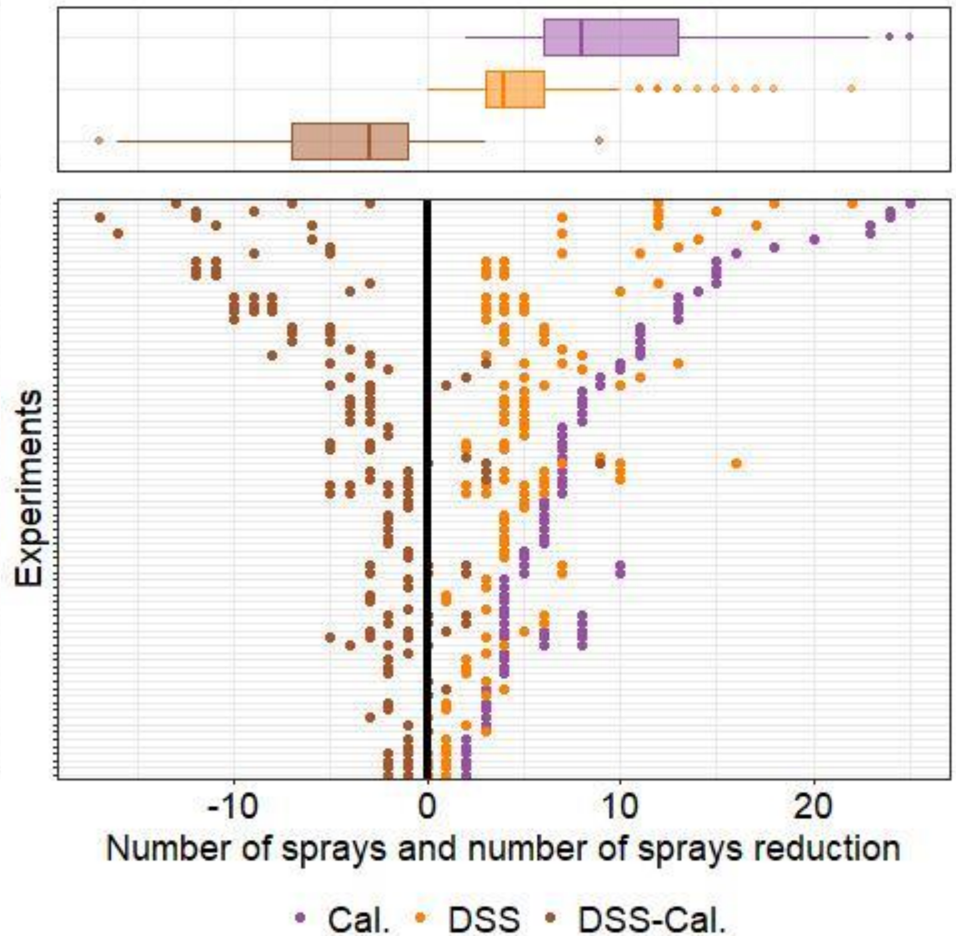
- **22** published **articles**
- **80** experiments
  - **80** untreated controls (**Unt.**)
  - **99** calendar-based strategies (**Cal.**)
  - **149** DSS-based strategies (**DSS**)

❑ **INLCUSION CRITERIA** per experiment:

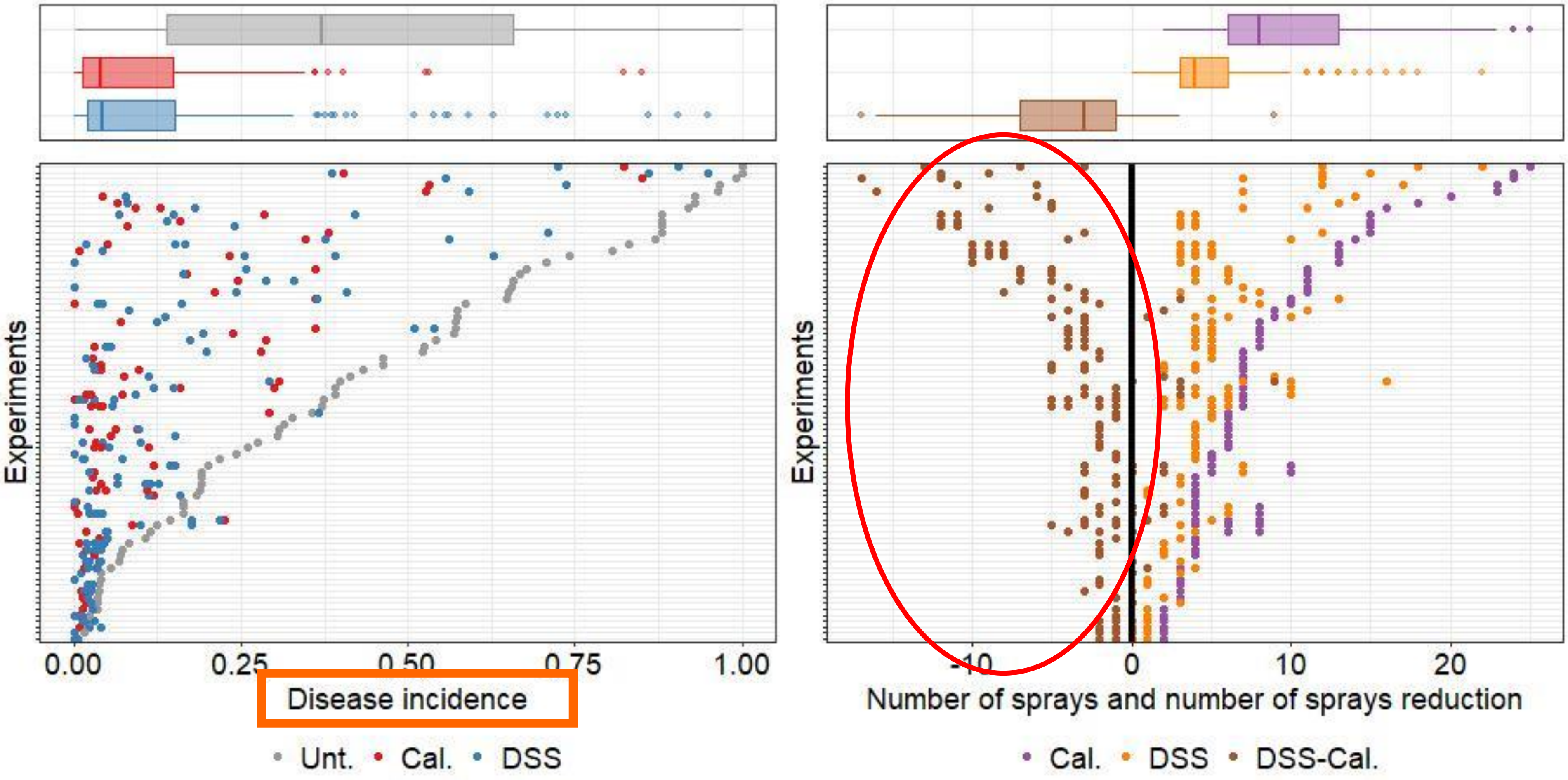
1. **One** untreated control (**Unt.**), **one** calendar-based strategy (**Cal.**) and **one** DSS-based strategy (**DSS**)
2. **Disease incidence** (i.e., the proportion of diseased organs)
3. **Sample size** (i.e., the total number of organs evaluated)
4. **Number** of fungicide **spray applications**

- 80 experiments
  - 80 untreated controls (**Unt**), 99 calendar-based strategies (**Cal**), 149 DSS-based strategies (**DSS**)

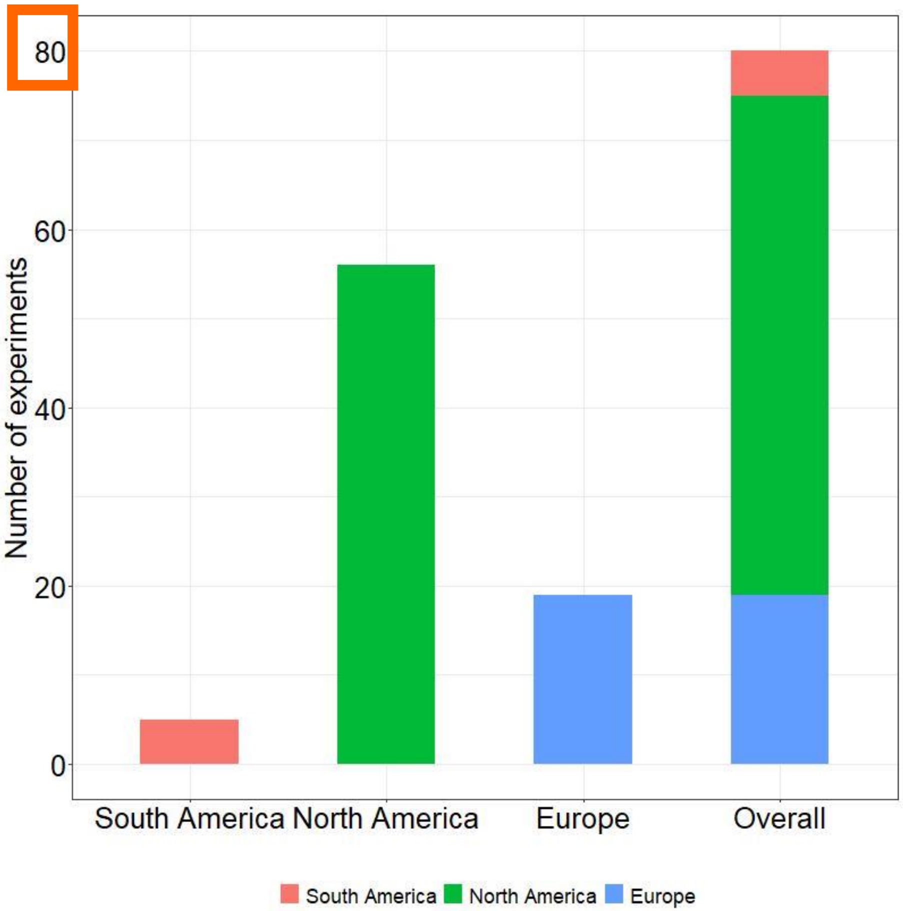




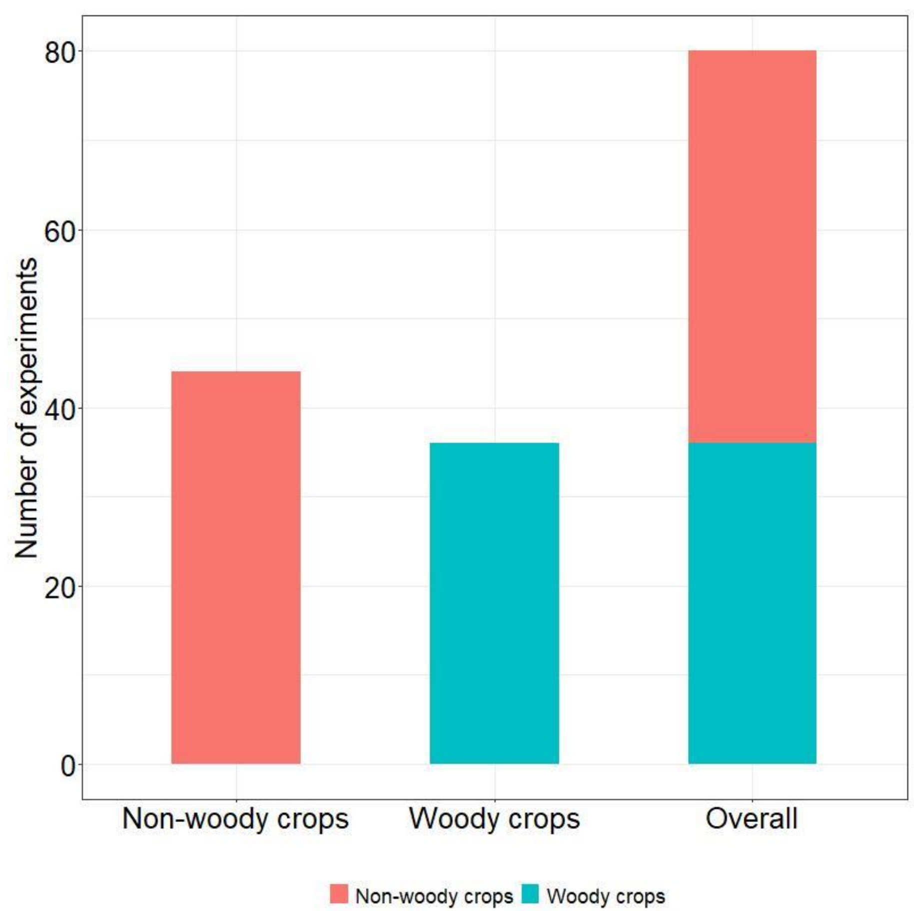
❑ 80 experiments
- 80 untreated controls (**Unt.**), 99 calendar-based strategies (**Cal.**), 149 DSS-based strategies (**DSS**)



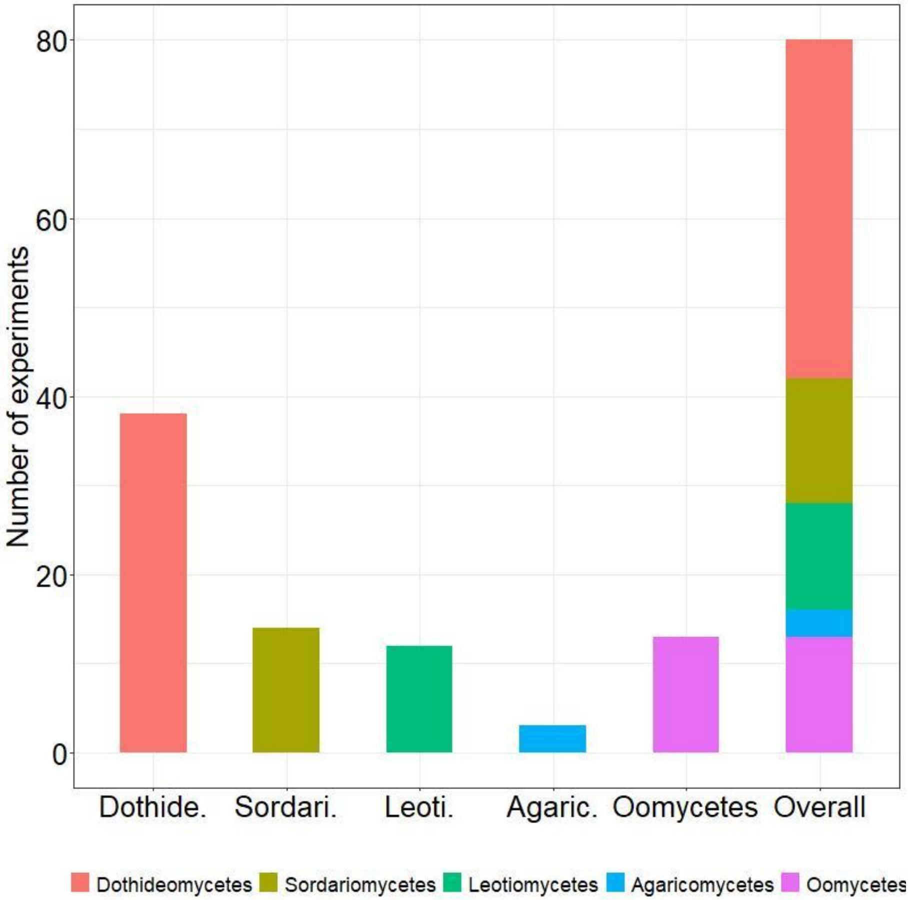
Location



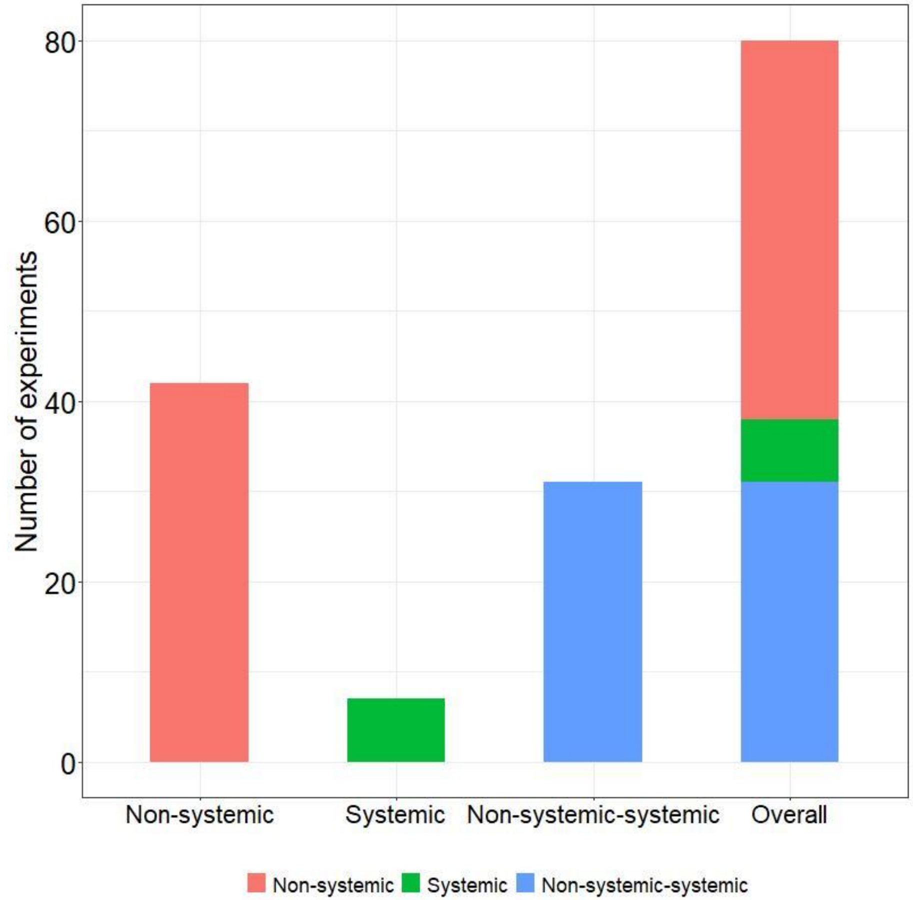
Crop



Pathogen



Fungicide categories



- **Two** independent **meta-analysis**:

  1. MI → **disease incidences** for **DSS**, **Cal** and **Unt**

  2. MIS → the **effect of the number of sprays** on **disease incidences** between DSS and Cal

- **Beta-binomial mixed-effect regression** modelling framework:

$$Y_{ij} \sim \mathrm{Bin}\,(n_{ij},\ \theta_{ij}),$$

$$\theta_{ij} \sim \mathrm{Beta}\,(\mu_{ij}\ \phi, (1-\mu_{ij})\ \phi),$$

- Y_{ij}: number of diseased organs in the plot j in the experiment i
- n_{ij} : organs evaluated
- θ_{ij}: disease incidence (probability)
- μ_{ij}: mean of disease incidence→ different in MI and MIS
- Φ: precision

- **MI** → MI_0 (MI_{loc} , $MI_{loc,int}$, MI_{crop} , $MI_{crop,int}$,MI_{pat}, $MI_{pat,int}$, MI_{fun} , $MI_{fun,int}$)

$$\operatorname{logit}(\mu_{ij}) = \log\left(\frac{\mu_{ij}}{1-\mu_{ij}}\right) = (\beta_0 + b_{0(\mathrm{i})}) + (\beta_{\mathrm{cal}} + b_{\mathrm{cal(i)}})\, I_{\mathrm{cal(ij)}} + (\beta_{\mathrm{dss}} + b_{\mathrm{dss(i)}})\, I_{\mathrm{dss(ij)}},$$

$$\begin{bmatrix} b_{0\,(\mathrm{i})} \\ b_{\mathrm{cal}\,(\mathrm{i})} \\ b_{\mathrm{dss}\,(\mathrm{i})} \end{bmatrix} \sim \mathrm{N}_3\left\{\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} \sigma_0^2 & \sigma_{0,\mathrm{cal}} & \sigma_{0,\mathrm{dss}} \\ \sigma_{0,\mathrm{cal}} & \sigma_{\mathrm{cal}}^2 & \sigma_{\mathrm{cal,dss}} \\ \sigma_{0,\mathrm{dss}} & \sigma_{\mathrm{cal,dss}} & \sigma_{\mathrm{dss}}^2 \end{bmatrix}\right\}$$

- **Disease Incidende Difference** (DID > 0) → $DID_{Cal\text{-}Unt}$, $DID_{DSS\text{-}Unt}$, $DID_{DSS\text{-}Cal}$

$$\begin{aligned} \mu_{Unt} &= \frac{\exp\{\beta_0\}}{1+\exp\{\beta_0\}}, \\ \mu_{Cal} &= \frac{\exp\{\beta_0+\beta_{\mathrm{cal}}\}}{1+\exp\{\beta_0+\beta_{\mathrm{cal}}\}}, \\ \mu_{DSS} &= \frac{\exp\{\beta_0+\beta_{\mathrm{dss}}\}}{1+\exp\{\beta_0+\beta_{\mathrm{dss}}\}}. \end{aligned}$$

$$\begin{aligned} \mathrm{DID}_{Cal-Unt} &= \mu_{Cal} - \mu_{Unt}, \\ \mathrm{DID}_{DSS-Unt} &= \mu_{DSS} - \mu_{Unt}, \\ \mathrm{DID}_{DSS-Cal} &= \mu_{DSS} - \mu_{Cal}, \end{aligned}$$

- **MI** → MI_0 (MI_{loc}, $MI_{loc,int}$, MI_{crop}, $MI_{crop,int}$, MI_{pat}, $MI_{pat,int}$, MI_{fun}, $MI_{fun,int}$)

$$\operatorname{logit}(\mu_{ij}) = \log\left(\frac{\mu_{ij}}{1-\mu_{ij}}\right) = (\beta_0 + b_{0(i)}) + (\beta_{cal} + b_{cal(i)}) I_{cal(ij)} + (\beta_{dss} + b_{dss(i)}) I_{dss(ij)},$$

$$\begin{bmatrix} b_{0(i)} \\ b_{cal(i)} \\ b_{dss(i)} \end{bmatrix} \sim N_3 \left\{ \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} \sigma_0^2 & \sigma_{0,cal} & \sigma_{0,dss} \\ \sigma_{0,cal} & \sigma_{cal}^2 & \sigma_{cal,dss} \\ \sigma_{0,dss} & \sigma_{cal,dss} & \sigma_{dss}^2 \end{bmatrix} \right\}$$

- **Disease Incidende Difference** (DID > 0) → $DID_{Cal-Unt}$, $DID_{DSS-Unt}$, $DID_{DSS-Cal}$

$$\mu_{Unt}^{P} = \frac{\exp\{\beta_0 + b_{0,new}\}}{1 + \exp\{\beta_0 + b_{0,new}\}},$$

$$\mu_{Cal}^{P} = \frac{\exp\{\beta_0 + b_{0,new} + \beta_{cal} + b_{cal,new}\}}{1 + \exp\{\beta_0 + b_{0,new} + \beta_{cal} + b_{cal,new}\}},$$

$$\mu_{DSS}^{P} = \frac{\exp\{\beta_0 + b_{0,new} + \beta_{dss} + b_{dss,new}\}}{1 + \exp\{\beta_0 + b_{0,new} + \beta_{dss} + b_{dss,new}\}}.$$

- **MIS→** MIS_0 (MIS_{loc} , $\text{MIS}_{\text{loc,int}}$, MIS_{crop} , $\text{MIS}_{\text{crop,int}}$,MIS_{pat}, $\text{MIS}_{\text{pat,int}}$, MIS_{fun} , $\text{MIS}_{\text{fun,int}}$)

$$\text{logit}\,(\mu_{ij}) = \log\left(\frac{\mu_{ij}}{1-\mu_{ij}}\right) = (\beta_0 + b_{0(\text{i})}) + (\beta_{\text{nspcal}} + b_{\text{cal(i)}})\ \text{nspcal(ij)}\ I_{\text{cal(ij)}}$$
$$+ (\beta_{\text{nspdss}} + b_{\text{dss(i)}})\ \text{nspdss(ij)}\ I_{\text{dss(ij)}},$$

$$\begin{bmatrix} b_{0\,(\text{i})} \\ b_{\text{cal}\,(\text{i})} \\ b_{\text{dss}\,(\text{i})} \end{bmatrix} \sim \text{N}_3 \left\{ \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} \sigma_0^2 & 0 & 0 \\ 0 & \sigma_{\text{cal}}^2 & 0 \\ 0 & 0 & \sigma_{\text{dss}}^2 \end{bmatrix} \right\}$$

- **Disease Incidende Difference** (DID > 0) → $\text{DID}_{\text{Cal-Unt}}$, $\text{DID}_{\text{DSS-Unt}}$, $\text{DID}_{\text{DSS-Cal}}$

$$\mu_{Unt} = \frac{\exp\{\beta_0\}}{1+\exp\{\beta_0\}},$$
$$\mu_{Cal} = \frac{\exp\{\beta_0 + \beta_{\text{nspcal}}\ \text{nspcal}\}}{1+\exp\{\beta_0 + \beta_{\text{nspcal}}\ \text{nspcal}\}},$$
$$\mu_{DSS} = \frac{\exp\{\beta_0 + \beta_{\text{dss}}\ \text{nspdss}\}}{1+\exp\{\beta_0 + \beta_{\text{dss}}\ \text{nspdss}\}}.$$

$$\mu^P_{Unt} = \frac{\exp\{\beta_0 + b_{0,\text{new}}\}}{1+\exp\{\beta_0 + b_{0,\text{new}}\}},$$
$$\mu^P_{Cal} = \frac{\exp\{(\beta_0 + b_{0,\text{new}}) + (\beta_{\text{nspcal}} + b_{\text{cal,new}})\ \text{nspcal}\}}{1+\exp\{(\beta_0) + (b_{0,\text{new}}) + (\beta_{\text{nspcal}} + b_{\text{cal,new}})\ \text{nspcal}\}},$$
$$\mu^P_{DSS} = \frac{\exp\{(\beta_0 + b_{0,\text{new}}) + (\beta_{\text{dss}} + b_{\text{dss,new}})\ \text{nspdss}\}}{1+\exp\{(\beta_0 + b_{0,\text{new}}) + (\beta_{\text{dss}} + b_{\text{dss,new}})\ \text{nspdss}\}}.$$

- **Bayesian inference → Stan (**https://mc-stan.org/)

  - Sampling from the posterior is based on **Hamiltonian Monte Carlo** (HMC) ('borrowed' from particle physics)

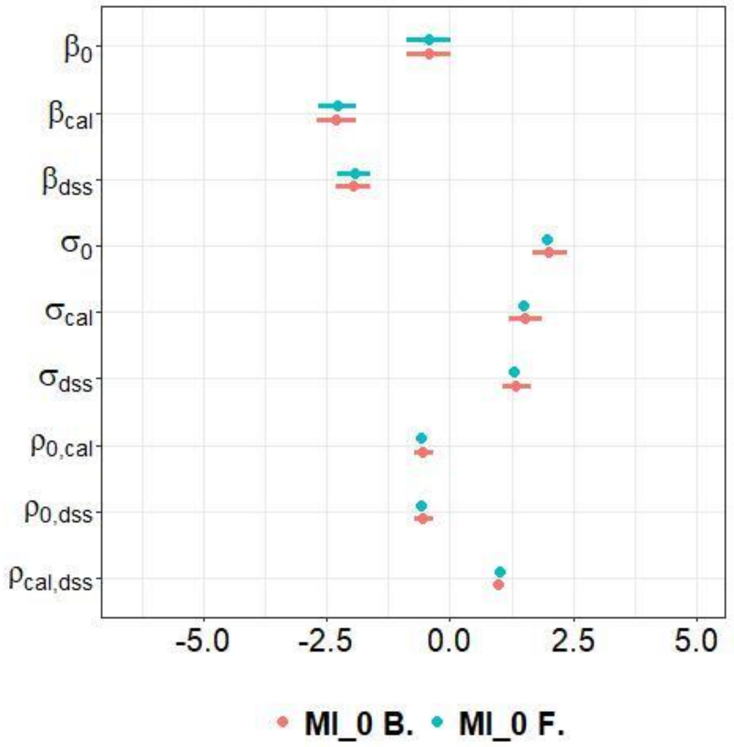
  - HMC can provide huge improvements in **computational efficiency** over conventional **Metropolis-Hastings and Gibbs sampling** (e.g. WinBUGS/JAGS), but mathematical foundations are more difficult to follow

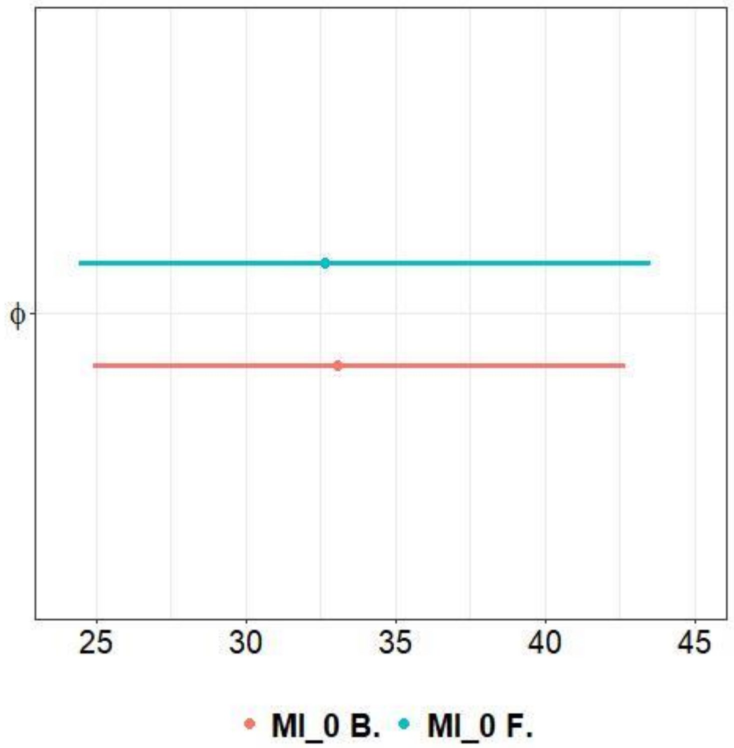
  - Models are defined by the user through **template files**, giving huge flexibility in model structure

  - Using **R**, the **brms** package allows fitting Bayesian multilevel linear and non-linear models in Stan using an intuitive high level syntax (similar to **lme4**)

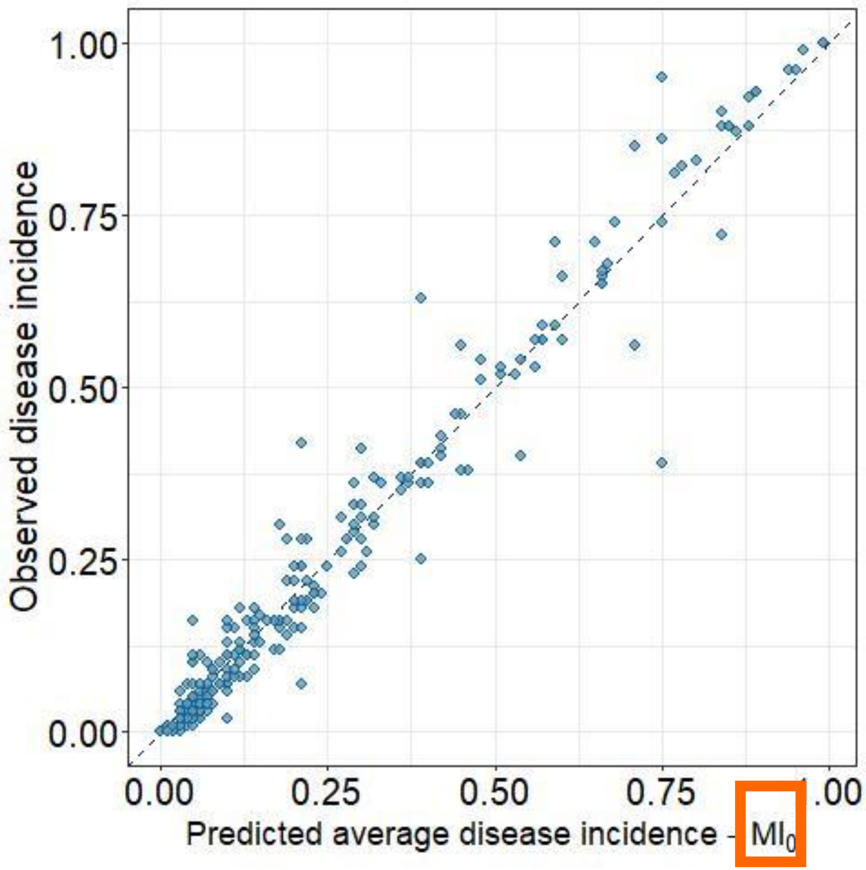
❑ Sensitivity analysis → Bayesian vs frequentist

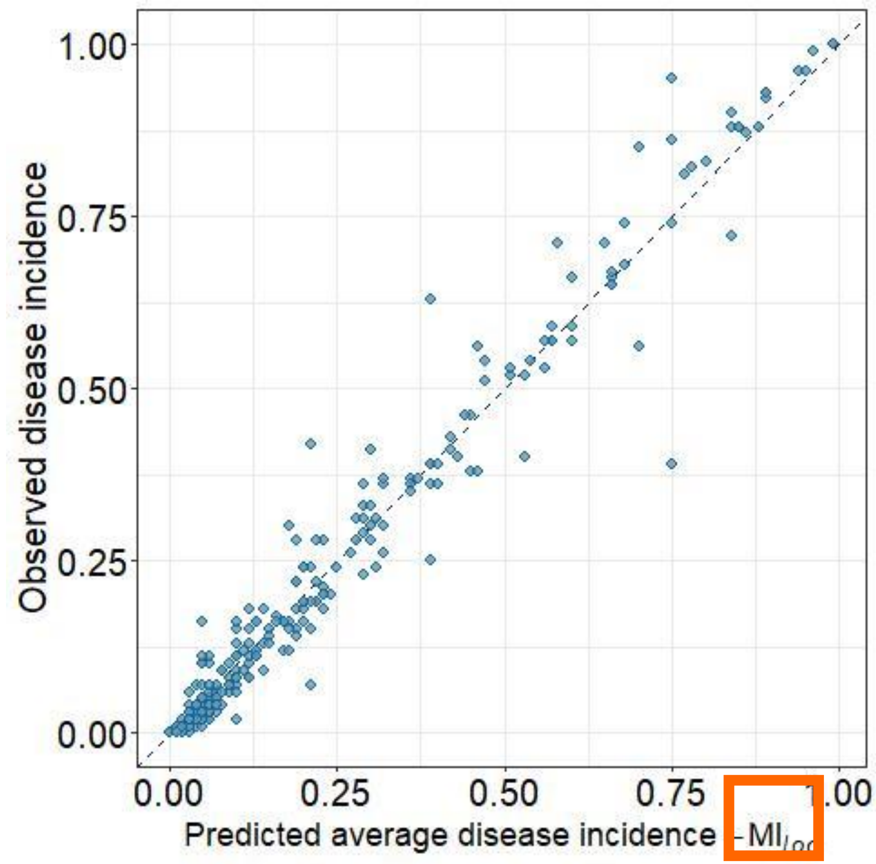
- Frequentist method by maximum likelihood through Laplace approximation using the R package **glmmTMB4**





❑ Model evaluation → Posterior predictive checks





Model selection

- Posterior predictive checks **(K (5)-fold-CV)**
- **elpd:** expected log pointwise predictive density
  - "The height (density) of of the probability distribution, given the model parameters, at the data point (pointwise) that were held-out (predictive)"

Table S8. K-fold cross-validation model selection values for the MIS models.

Model	elpd_kfold	SE_elpd_kfold	Δelpd_kfold (A)[a]	ΔSE_elpd_kfold (B)[b]	$\left\lvert\frac{A}{B}\right\rvert$
MIS_0	-1731.5	30.6	–	–	–
MIS_{loc}	-1745.3	31.7	14.3	14.1	1.0
$MIS_{loc,int}$	-1741.1	31.6	10.2	15.7	0.6
MIS_{crop}	-1730.6	28.9	-0.4	6.0	0.1
$MIS_{crop,int}$	-1734.0	29.8	3.0	5.0	0.6
MIS_{pat}	-1724.2	29.2	-6.8	6.4	1.1
$MIS_{pat,int}$	-1720.3	30.1	-10.6	7.3	1.5
MIS_{fun}	-1735.3	30.4	4.3	1.6	2.8
$MIS_{fun,int}$	-1713.1	33.9	-17.9	12.9	1.4

[a] Difference between the baseline model (MIS_0) and the models including moderator variables

[b] Difference in models are considered not meaningful if $\left\lvert\frac{A}{B}\right\rvert \leqslant 4$

RESULTS

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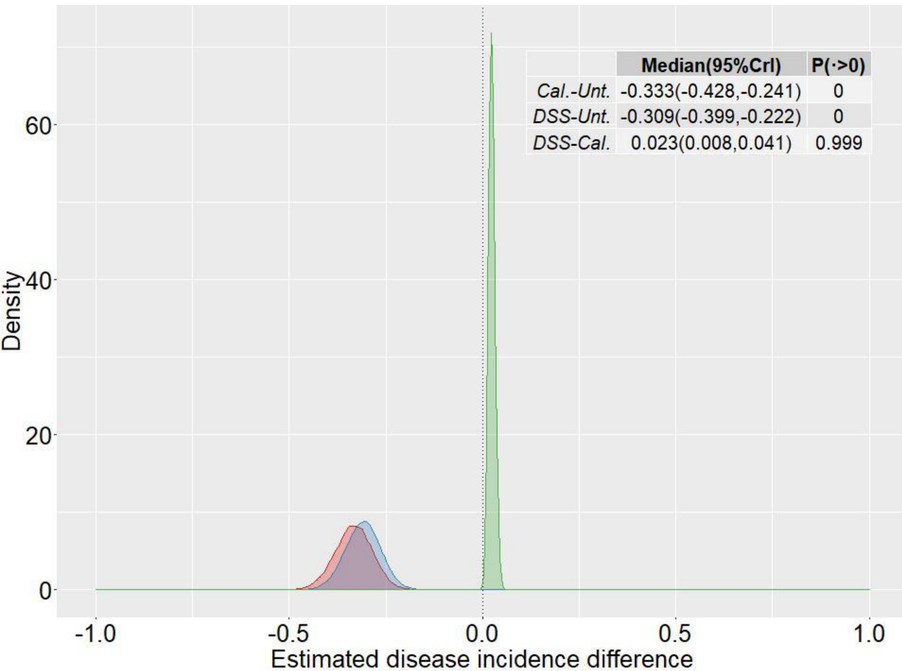
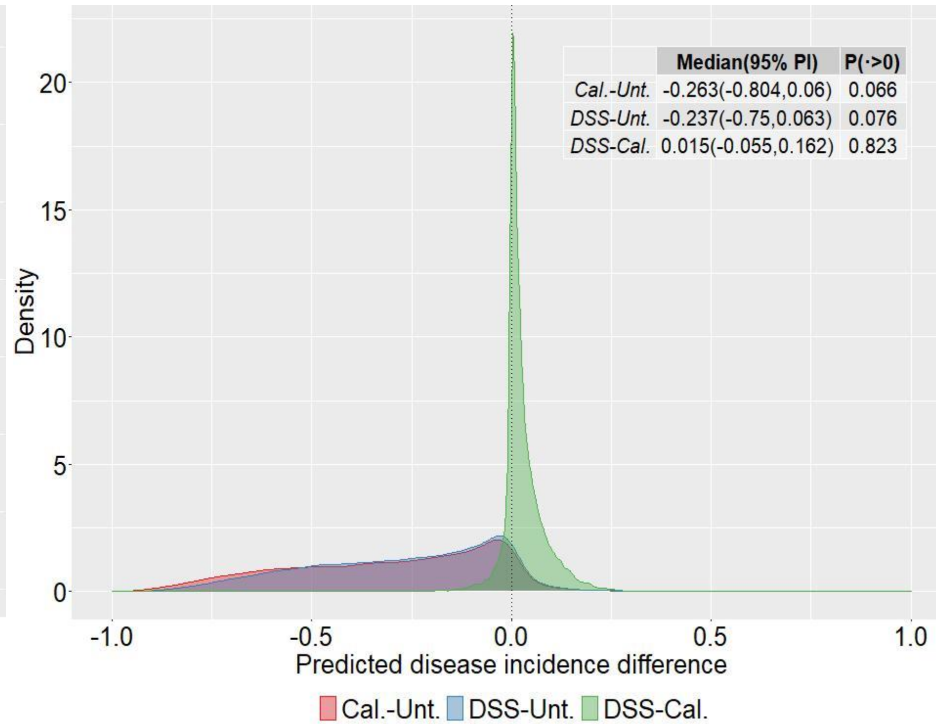
Meta-analysis MI (disease incidence)

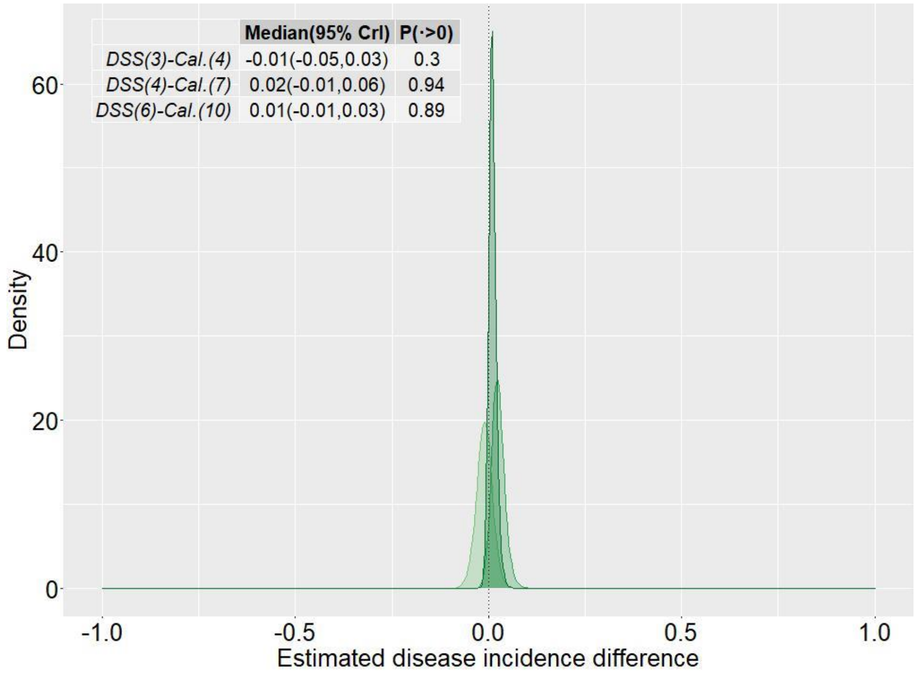


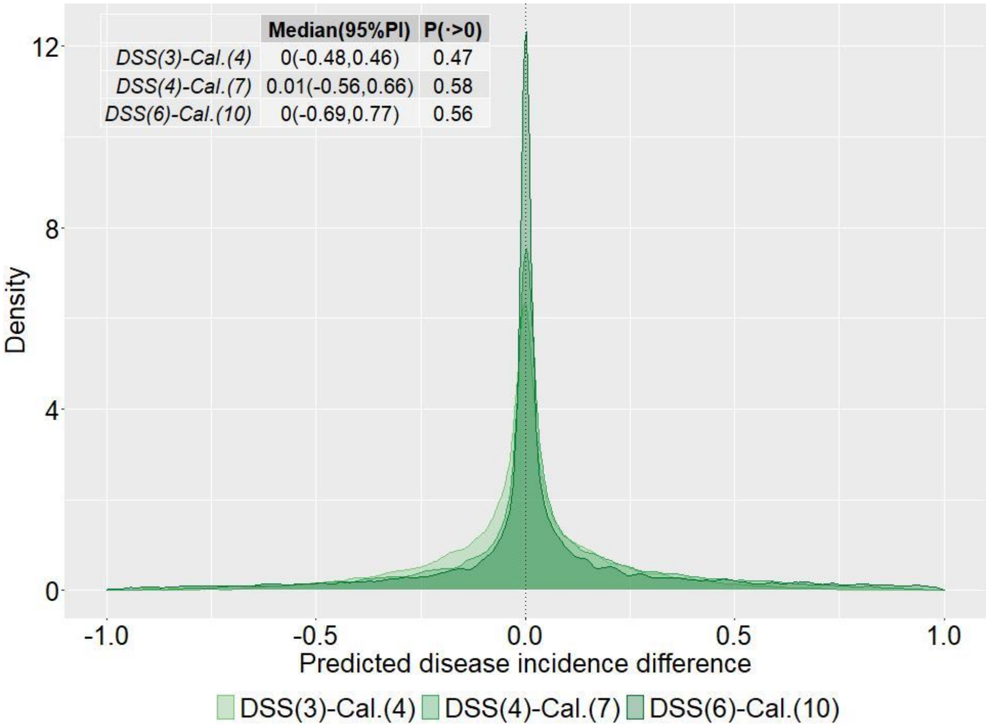


Prediction intervals

- plausible range of values that could be obtained in a new experiment
- Interval length depends on the magnitude of the variability between experiments

- Meta-analysis MIS (number of sprays vs disease incidence)



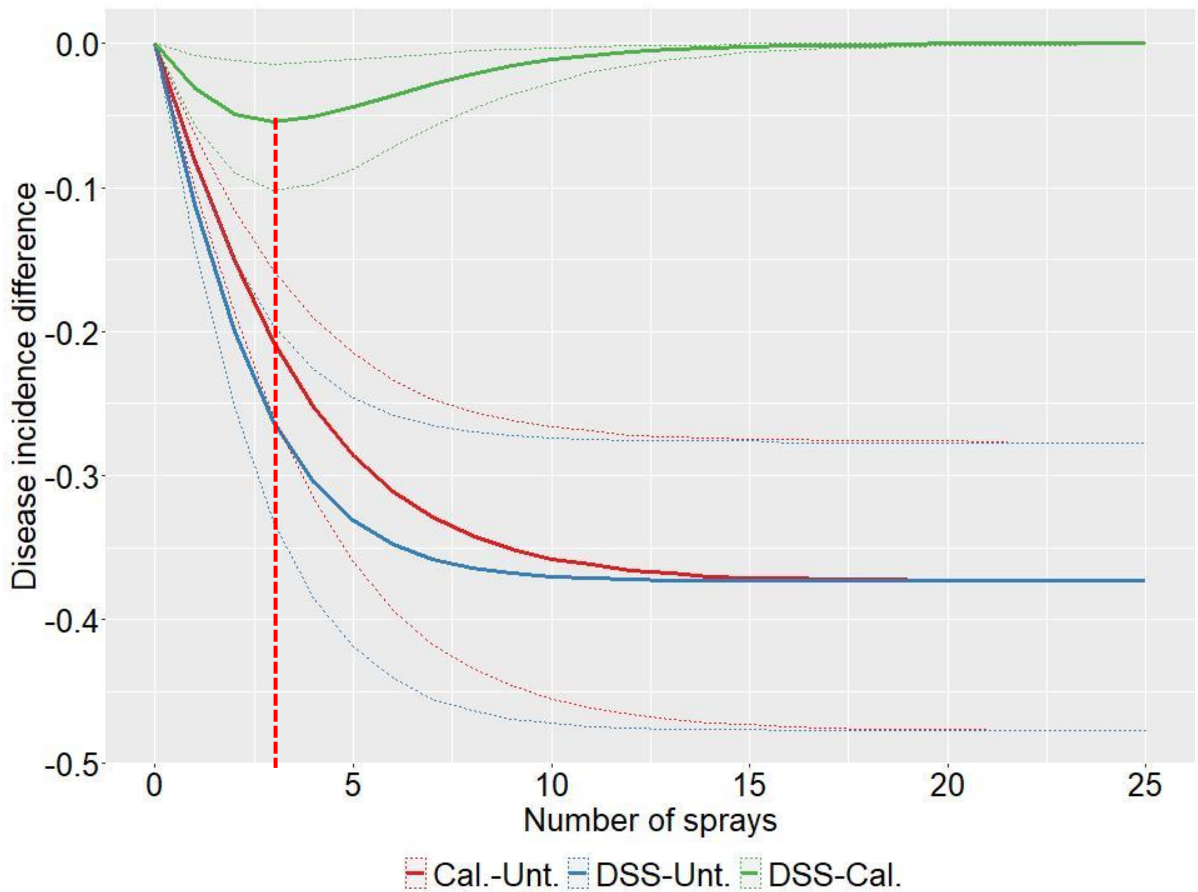


- Number of sprays:
  - ***nspcal* = 4 vs. *nspdss* = 3** (Q_1)
  - ***nspcal* = 7 vs. *nspdss* = 4** (median)
  - ***nspcal* = 10 vs. *nspdss* = 6** (Q_3)

- The difference between the **two medians** corresponds to a 43% reduction in the number of sprays with the DSS strategy compared to the calendar based-strategy

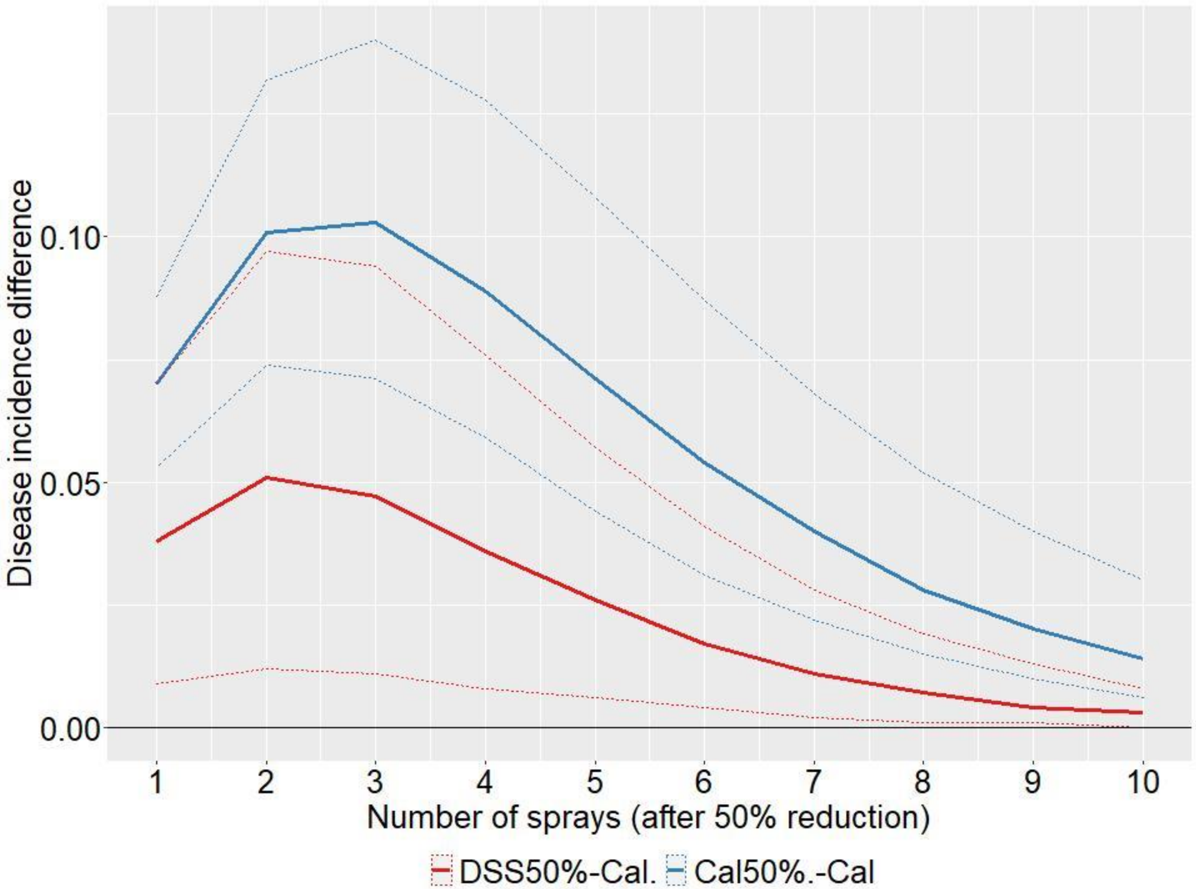
RESULTS

- Meta-analysis MIS (number of sprays vs disease incidence)



- For a given number of sprays, DSS-based fungicide programs were equally and even more effective (by up to 5.5%) for disease control

- Meta-analysis MIS (number of sprays vs disease incidence)



- Two comparisons:
  - the 50% reduction was achieved by adopting a DSS-based strategy (scenario DSS50%)
  - the 50% reduction was achieved by adopting a Cal-based strategy (scenario Cal50%)

CONCLUSIONS

- The goal of a 50% reduction in the number of fungicides (as envisioned by the 'from farm to fork' strategy of the European Green Deal11) is not a utopia
- DSS can play an important role in reducing fungicide use while maintaining a high level of crop protection
- Fungicide use in agriculture can be further reduced if DSS are integrated with other management strategies
- The efficacy of DSS is linked to their proper development, validation and implementation in the field
- A limitation in the number of applications is also essential for the effective management of fungicide resistance

- Our work…
  - makes use of **meta-analysis** in the context of **agricultural sciences** to answer a **policy question**
  - considers **Bayesian** inference (hierarchical structure)→ **Stan** allows an **easy** and **efficient** implementation
  - Includes **quality standards** that guarantee the **robustness** of the conclusions **drawn**:
    - Comprehensive procedure to perform systematic review
    - Assessment of different modelling scenarios
      - Beta-binomial (overdispersion)
      - Random-effects (heterogeneity)
      - Model evaluation and model selection
    - Sensitivity analysis

Merci beaucoup pour votre attention