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INSTITUT
DE RADIOPROTECTION
ET DE SÛRETÉ NUCLÉAIRE

Enhancing nuclear safety

DEPOSITION OF AIRBORNE RADIONUCLIDES DURING FOGGY DAYS



Germany Isar Nuclear Power Plant 17zoom.net

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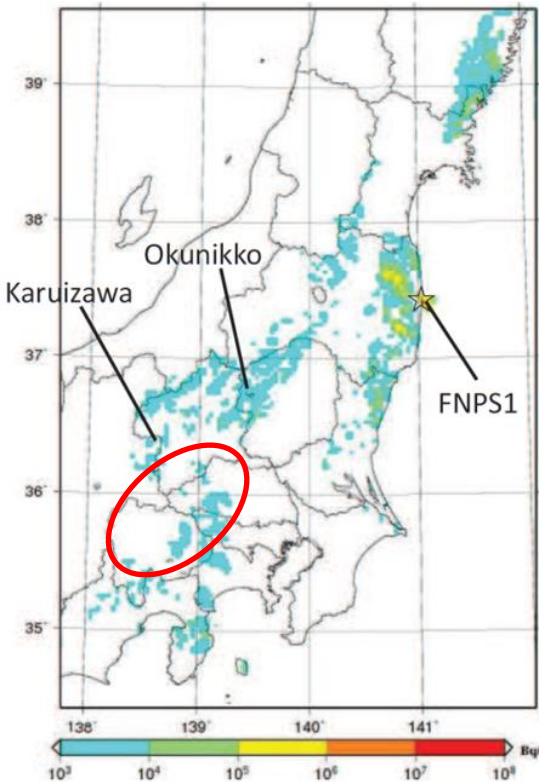
For cooling purpose, nuclear power plants (NPP) are located near water bodies, either near coastal shore or riverside. In fall and winter, fogs are frequent and localized in the surrounding areas



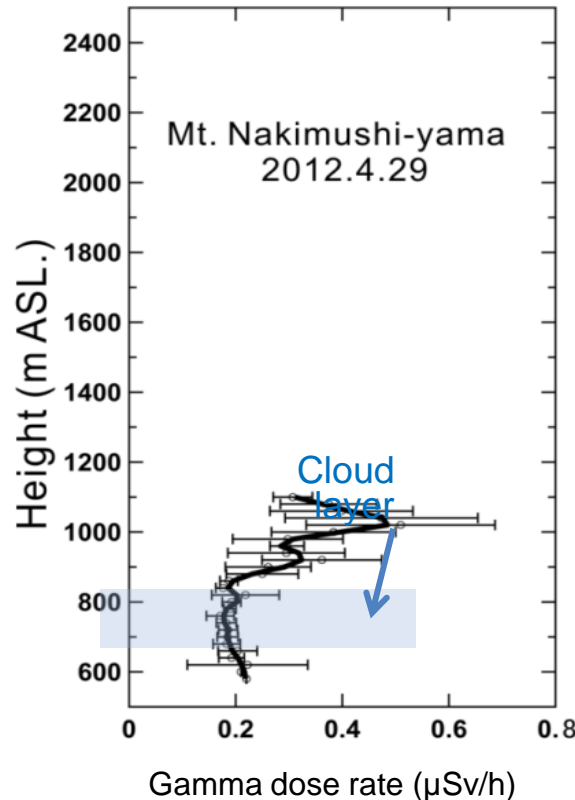
What would be deposited in the near field if an accident release of radionuclides occurs during a foggy day?

Several field observations were published after the FD1-NPP accident with regard to fog/cloud deposition to explain high contamination levels where no significant rain had occurred. This was particularly demonstrated for high altitude sites embedded by clouds when the radioactive plume arrived

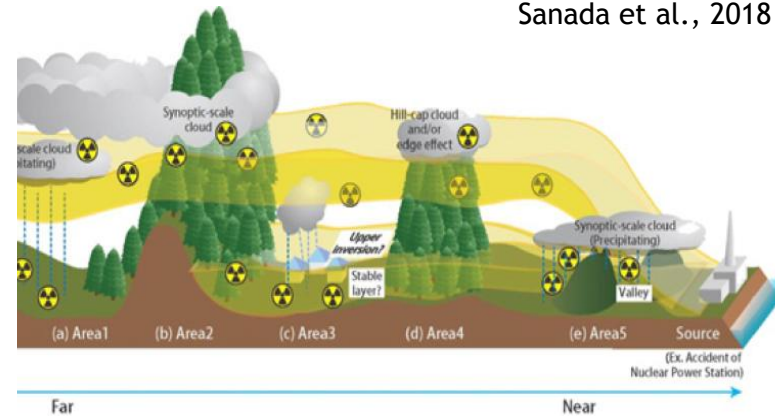
Katata et al., 2014, 2015



Hososhima & Kaneyasu, 2015



Sanada et al., 2018



“... In-cloud scavenging was the most dominant mechanism of radio-Cs deposition, followed by dry deposition and fog deposition over the entire land area.”
 Kajino et al. 2019

- ❑ In case of a nuclear accident, deposition of airborne radionuclides is the key parameter to assess the radioactive contamination of the environment.
- ❑ Radionuclide deposition is also used to take proper protective actions to limit health consequences by ingestion of contaminated foodstuff or to refine evacuation zones or restricted areas.
- ❑ Atmospheric deposition models used in emergency situation deal with dry and wet processes but wet deposition usually refers only to rain.
 - What are the main parameters to take into account for fog deposition?
 - Is fog deposition negligible / similar compare to dry deposition?
 - Can it be a matter of a drying-up of the air mass and additionally a contributor to the decrease in the concentration of aerosol-bound radionuclides?

- Transfer of airborne contaminants to plants are favored by wet deposition of fog droplets because the stomata opening is sensitive to the ambient moisture content
- After deposition water will evaporate but dissolved matters or insoluble particles will stay on the surfaces
- Fog droplets are bigger than most common aerosols \Rightarrow higher deposition velocity
- Fog droplets are more concentrated than rain drops because less diluted by condensation of H_2O vapor
- Fog droplets can also interact with interstitial aerosol (not yet activated)
- Dispersion and deposition models are using a deposition velocity (concept) defined by:

$$V_d \text{ (m/s)} = \text{Flux} / \text{Concentration}$$

$$Vd \text{ (m/s)} = F_w / LWC$$

with F_w the water deposition flux ($\text{g/m}^2/\text{s}$) = $\Delta m/\Delta t$ and LWC the *Liquid Water Content* (g/m^3)

$$Vd = Vds + Vdt$$

(Dollard and Unsworth, 1983)

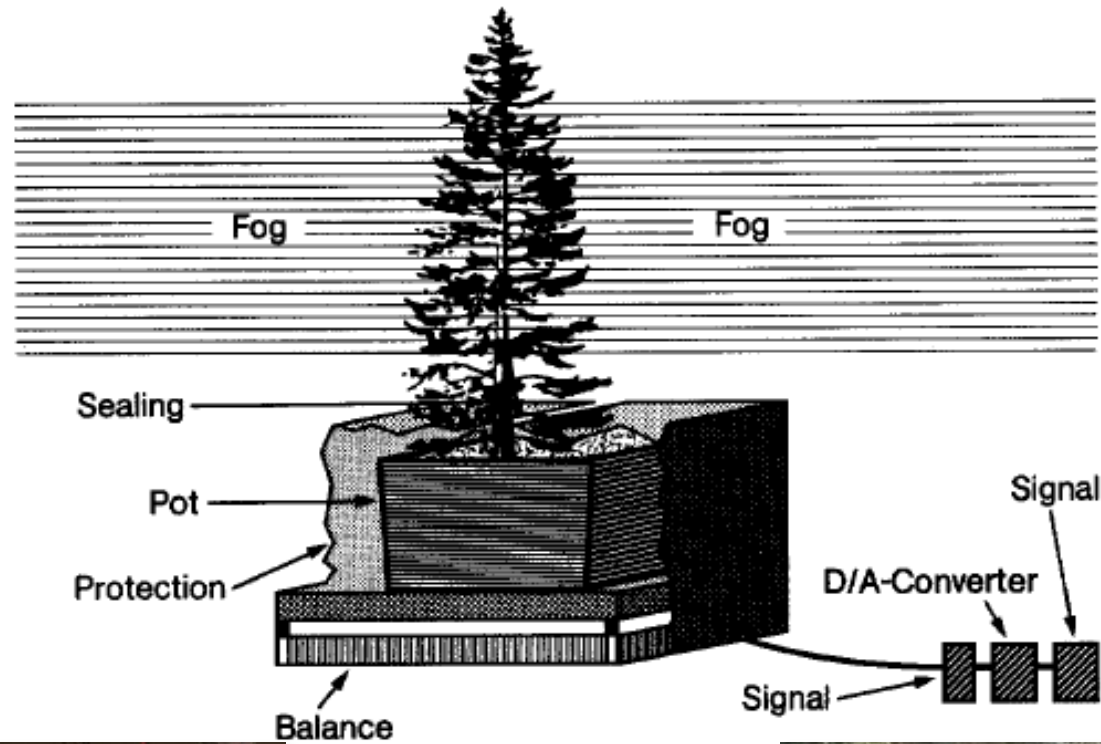
with Vds : sedimentation velocity associated to the droplet size distribution,

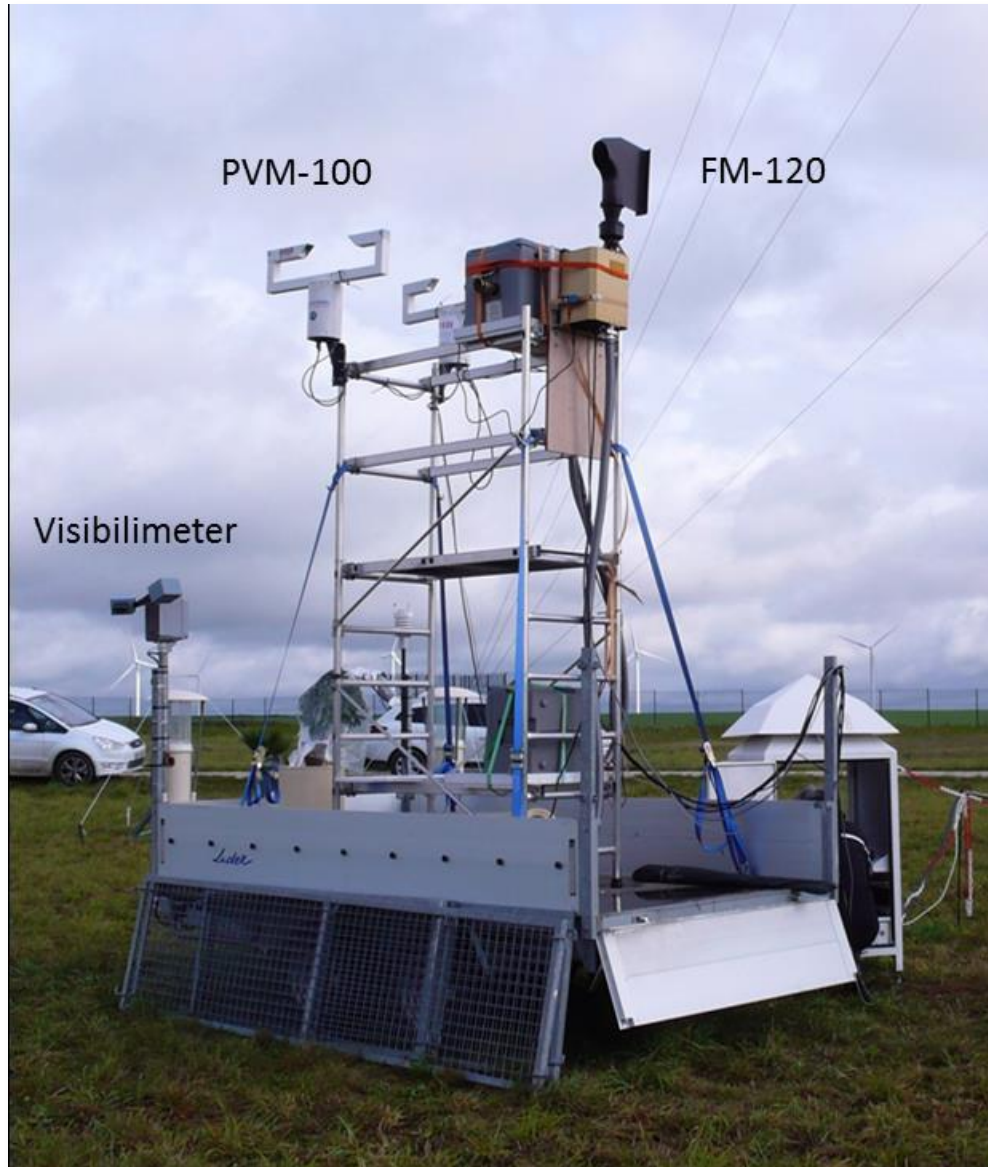
and Vdt : turbulent impaction velocity (even at low wind speed) as a function of deposition surface features (height, roughness, density of plant, 2D or 3D structures...)

■ Problems:

- The turbulent impaction component (Vdt) is not easily measurable or often measured on a routine basis,
- The fog water deposited amount cannot be measured neither by usual rain gauges nor by rain radar and remains most often unknown (called “occult deposition”)

Adapted from that proposed by Trautner and Eiden (1988)

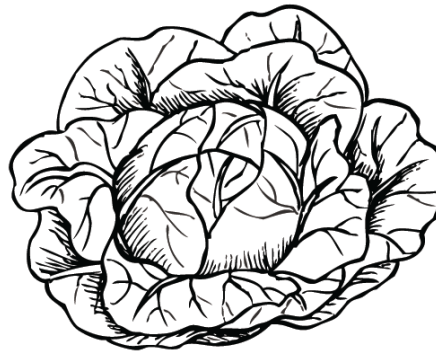
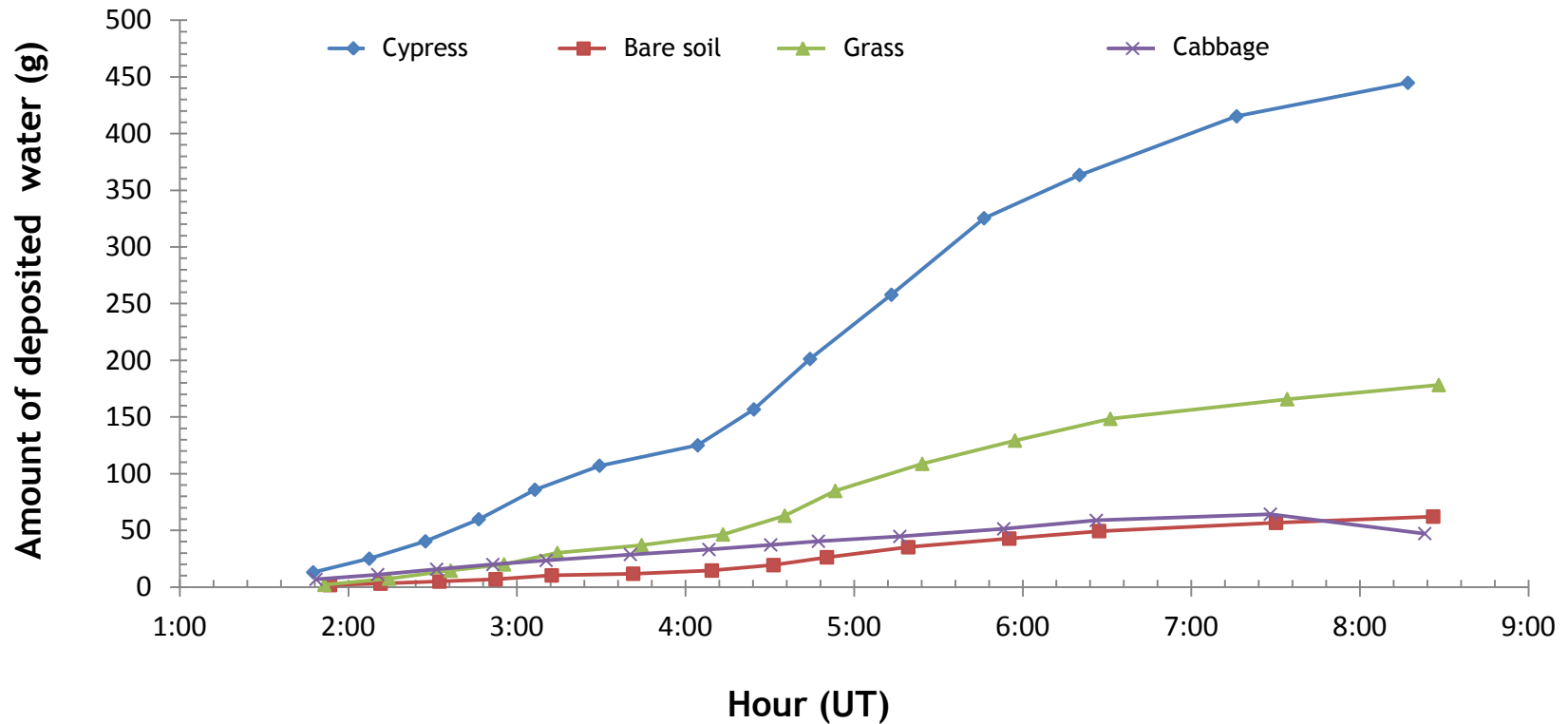


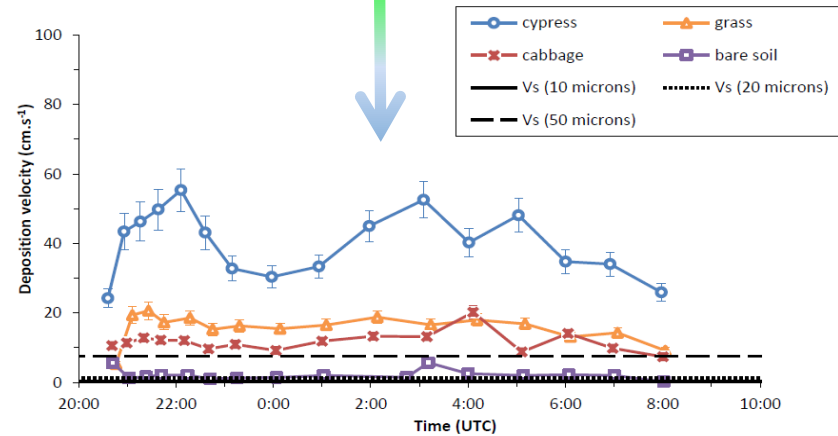
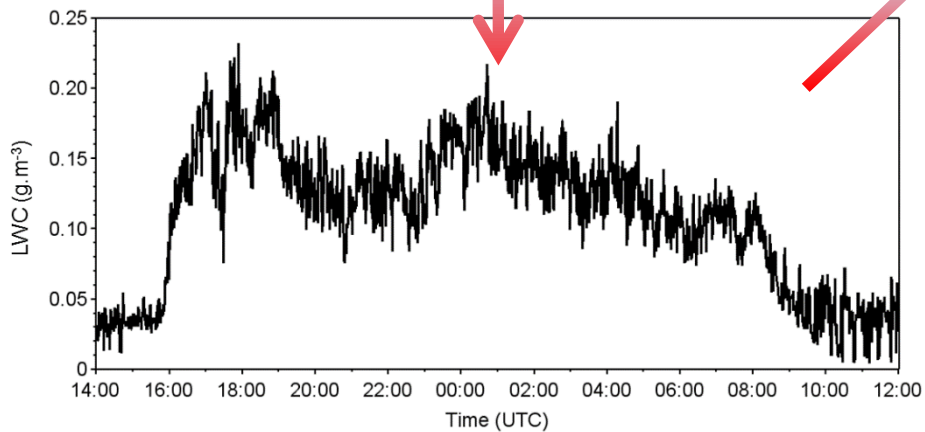
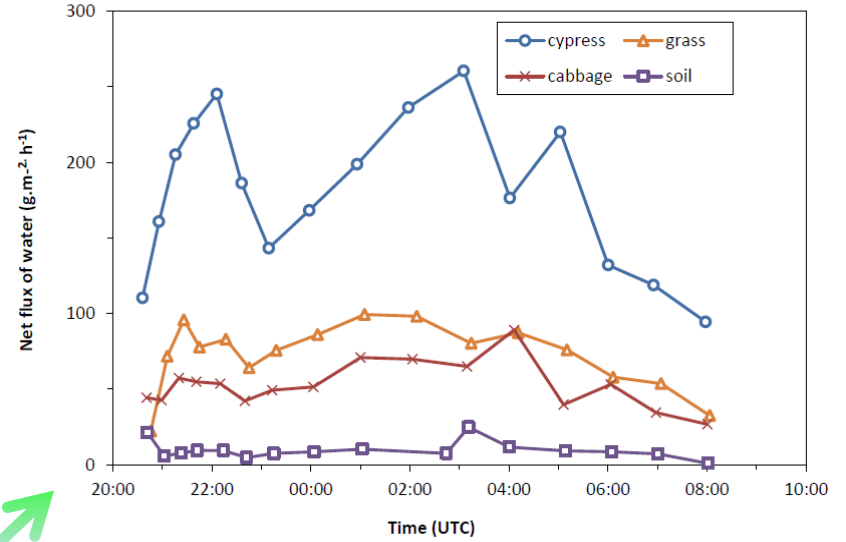
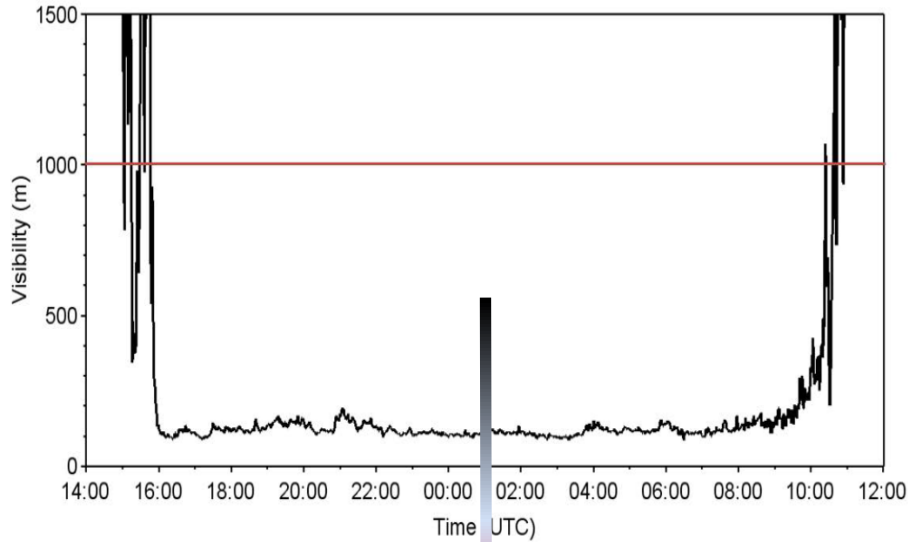


EVIDENCE OF DEPOSITION OF FOG DROPLETS ON PLANT



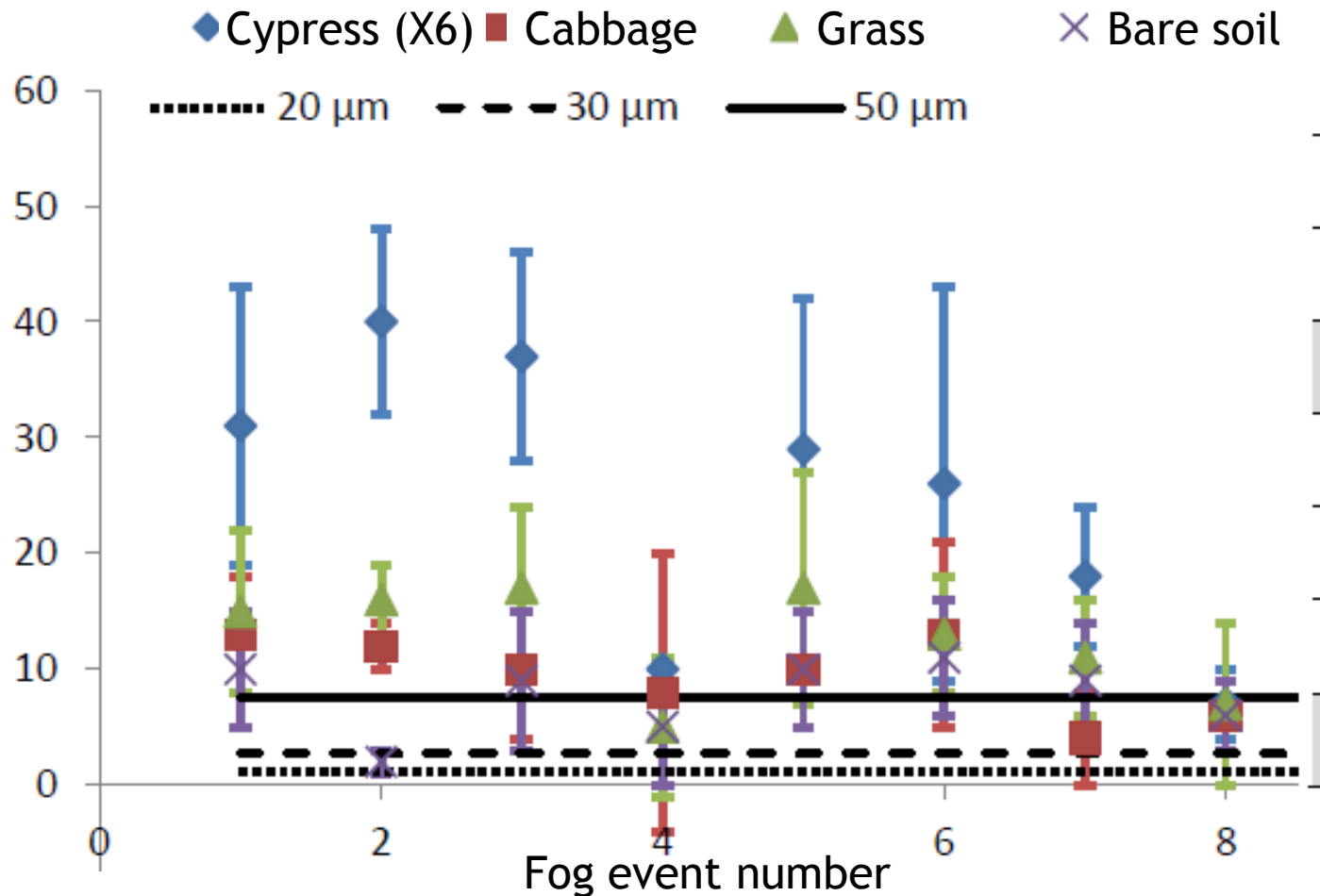
Cumulative fog water amount 31/10/2015



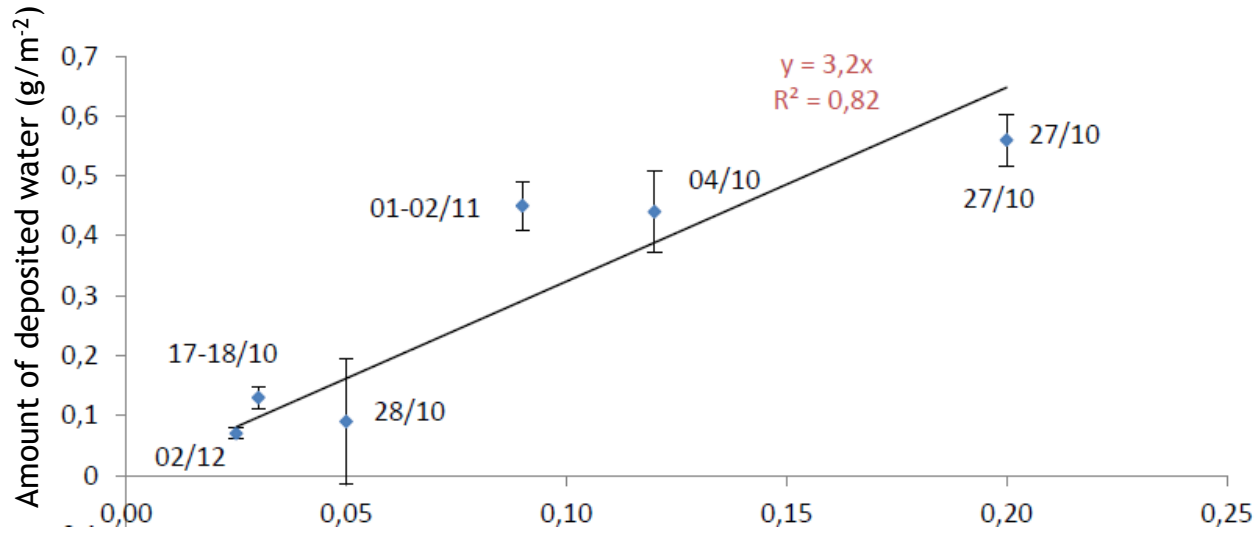


Jackie Tav et al. Determination of Fog-Droplet Deposition Velocity from a Simple Weighing Method, *Aerosol and Air Quality Research*, 18: 103–113, 2018.

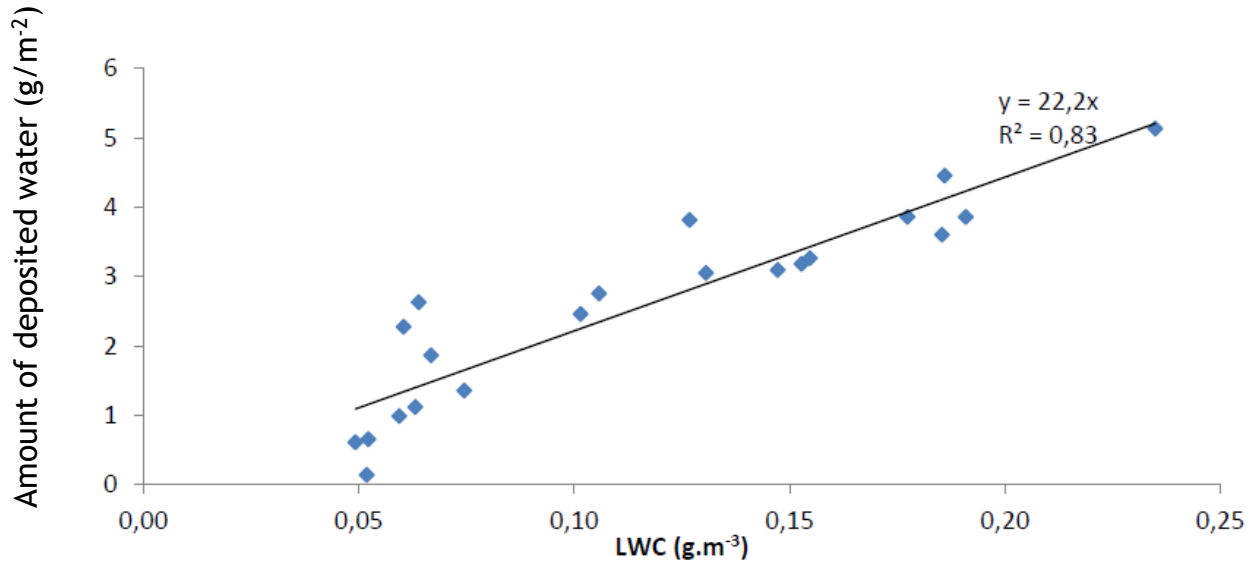
Surface	Vd (cm.s ⁻¹)
Cypress	40.0
High Grass	15.7
Cabbage	11.7
Bare soil	2.2



$$Vds = \frac{(\rho_p - \rho_{air}) \times d_p^2 \times g \times C_c}{18 \times \mu_{air}}$$
 is given for 20, 30, and 50 μm for comparison. The difference with the « measured » deposition velocity is attributed to the turbulent component of the deposition velocity Vdt



Bare soil



Cypress

Bare soil

Cypress

For $LWC < 0.1 \text{ g/m}^{-3}$ there is no clear difference between deposition surface but this could result from a sensitivness limit in weighing

CONTRIBUTION OF FOG TO SEASONAL RN DEPOSITION IN FRANCE

Autumn and Winter 2014-2015-2016, northeastern part of France

BARE SOILS

	Water amount (L/m ²)	[¹³⁷ Cs] (mBq. L ⁻¹)	¹³⁷ Cs deposition (mBq/m ²)	²¹⁰ Pb deposition (mBq/m ²)
Fog	0.65	0.92	0.55	863
	4.7	0.17	0.8	332
	0.6	0.32	0.12	138
Rain	285	0.045	13	21060
	156	0.017	3	5810
	192	0.017	3	5200
Fog / Rain	0,15 %	X 20		
	2 %	X 10		
	0.3 %	X 19		
Fog / Total fallout			5 %	4 %
			29 %	6 %
			4 %	2.6 %

1st Campaign

Nov. 2014-Feb. 2015

2nd Campaign

Oct. 2015-Dec. 2015

3rd Campaign

Oct. 2016-Dec. 2016

Dispersion and deposition models used in emergency situation do not consider the aerosol size to vary with time or distance.

Fog deposition is often qualified as « occult » because the amount is low and cannot be registered either by usual rain gauges or from rain radars. As a result fog deposition is rarely considered in deposition model.

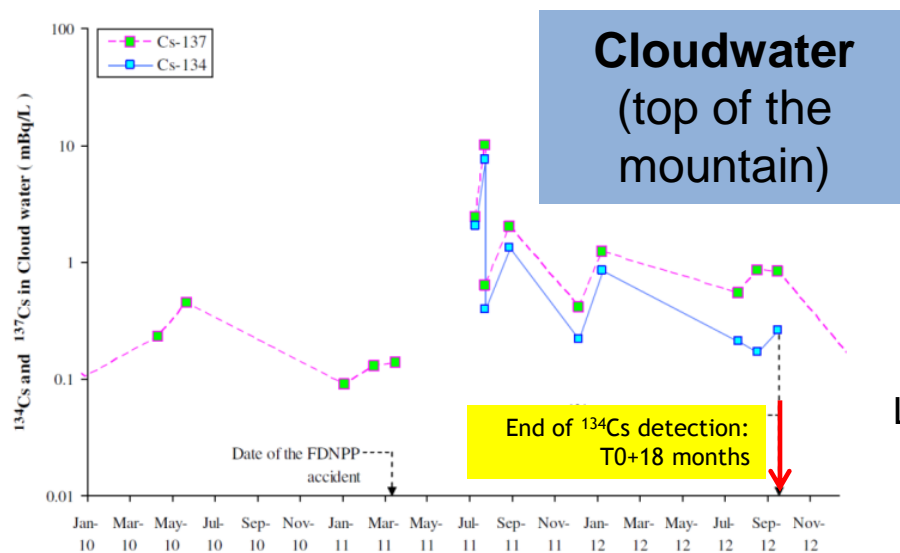
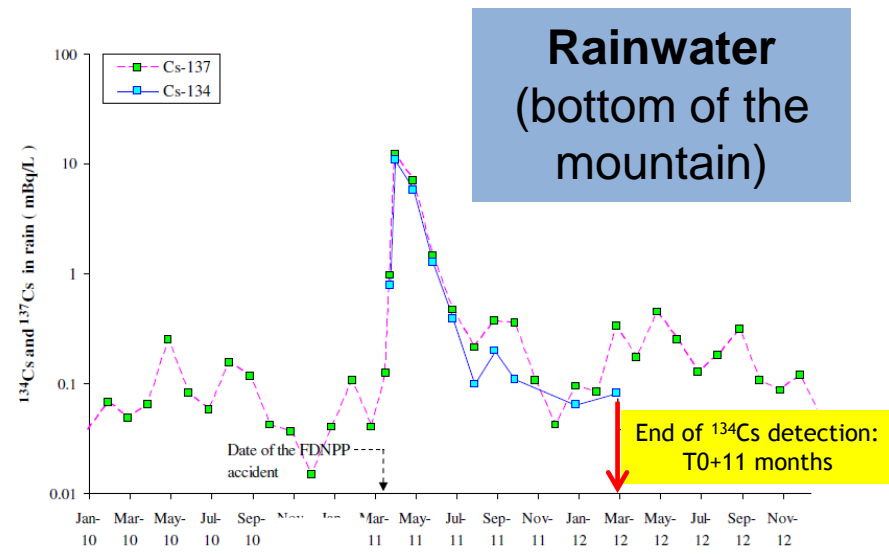
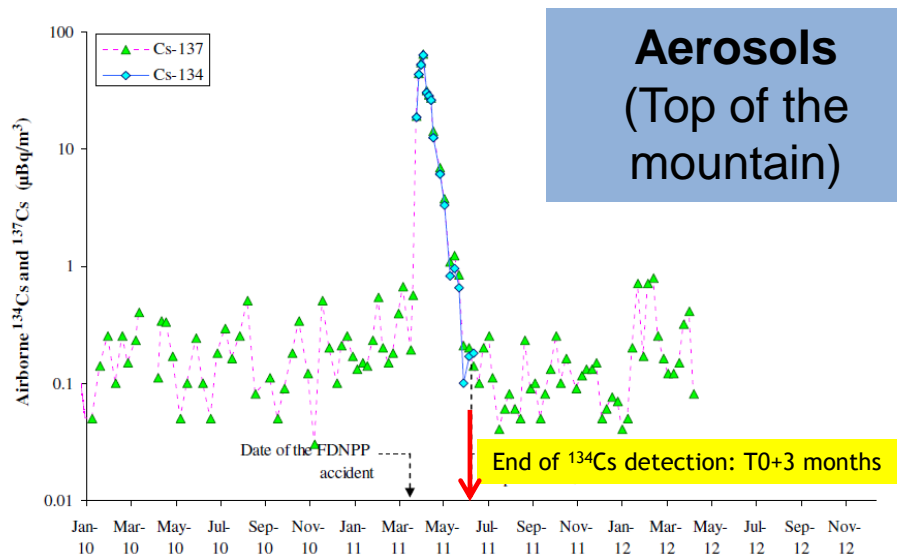
Fog deposition occurs by turbulent diffusion and in addition gravitational settling when the droplet size increases

As for dry deposition of aerosols, deposition velocities is a concept used in droplet deposition velocities as a key parameter used in models to assess the contamination of the environment. It depends on deposition surface features: and when dealing with plant on physiological aspects like stomata opening. range 1 - 100 cm.s⁻¹

Despite some differences between fog and cloud (droplet size distribution, turbulent motion) cloud deposition can help to assess the deposition velocity:

Rain scavenging results schematically from both in-cloud and below-cloud scavenging. Because of the high efficiency of the below cloud scavenging of aerosol by rain, it is assumed that after a while and supposing that the air mass is not renewed then the aerosol concentration in rain water will reflect the By comparison with rain, the aerosol scavenging by fog is similar to what happens in cloud while

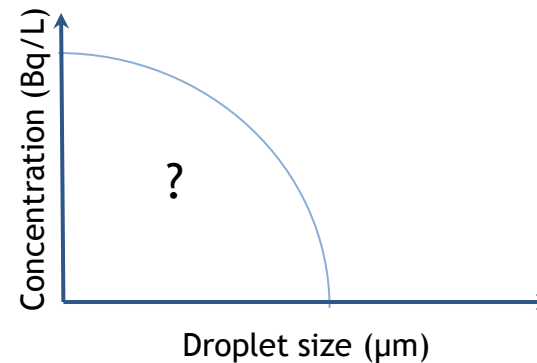
Activity levels of radioactive cesium isotopes (^{134}Cs and ^{137}Cs) in aerosols, rain and cloud water in France



$T_{1/2} \text{ } ^{134}\text{Cs} = 2 \text{ y}$
 $T_{1/2} \text{ } ^{137}\text{Cs} = 30 \text{ y}$

Long lasting ^{134}Cs detection in cloud water → higher concentration

- ❑ Characterization of the deposition velocity for marine fog droplets and associated radionuclides
- ❑ The droplet size is a key factor for deposition modeling and assessment, both regarding:
 - Deposition velocity (may be derived from deposition of dry aerosols)
 - Concentration in the fog water vs size (this parameter remains aggregated and unknown)

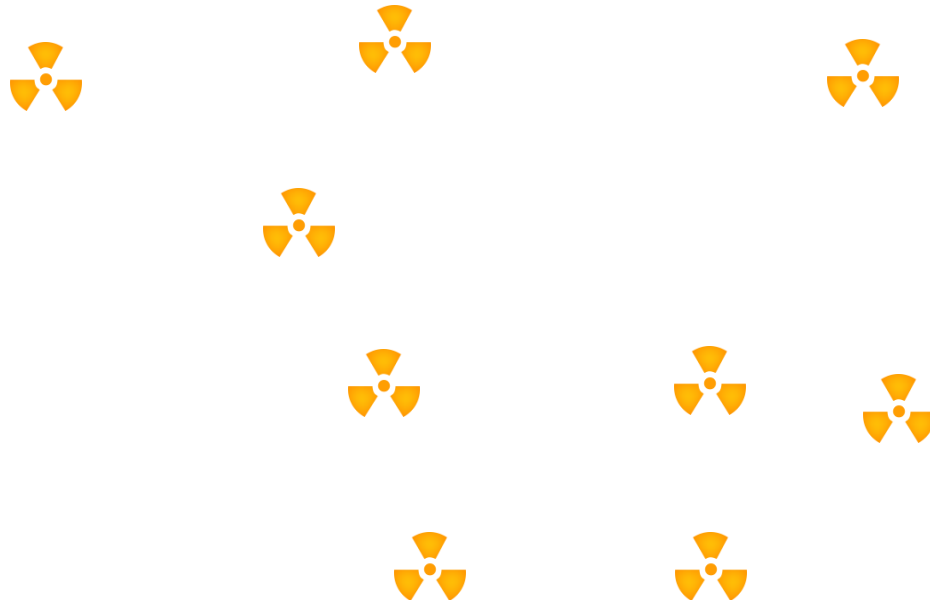


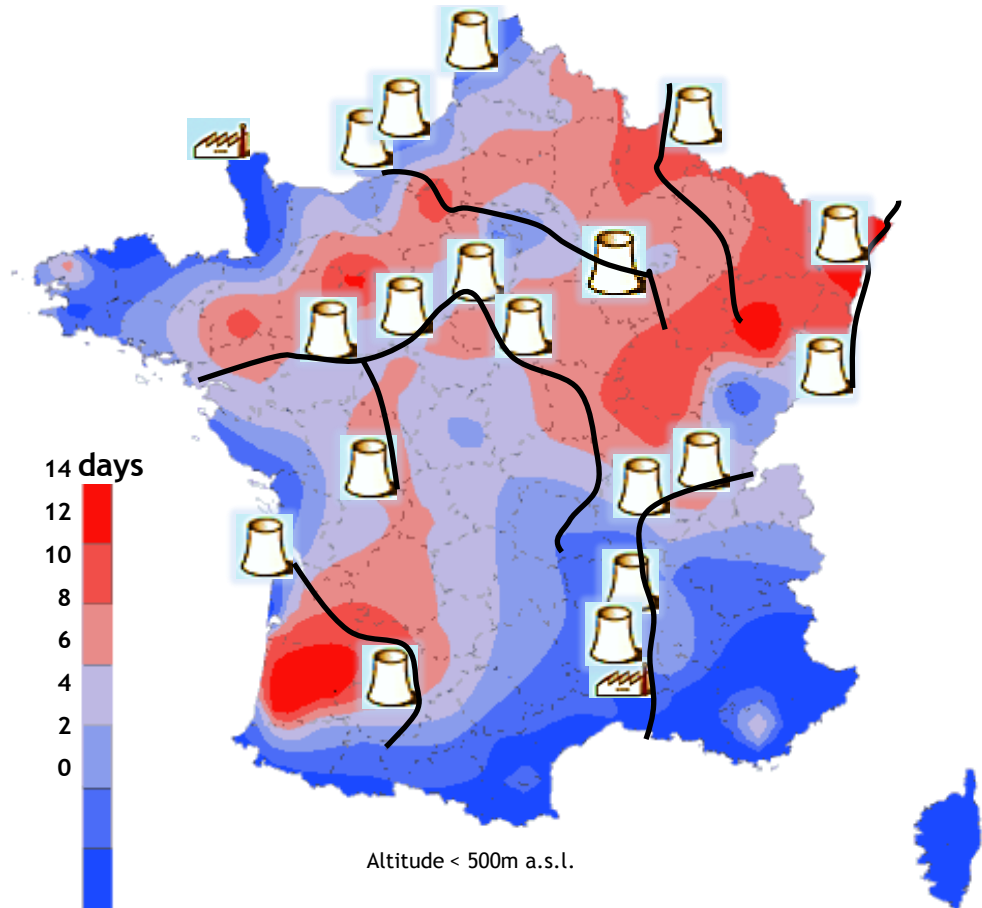
- ❑ Study of the role of the surface type on fog deposition: bare soil, short vegetation, crops, buildings (with regard to turbulent impaction and deposition)
- ❑ Study of the “Rainout coefficient”:
$$R = \frac{[RN]_{Fog\ water}}{[RN]_{Air}}$$
 - Provide a rapid assessment of the radionuclide fog deposition in case of emergency
- ❑ Comparison of fog RN deposition with other deposition (dry, rain) processes and quantification of its contribution to the global deposition budget

- If a fog event occurs at the same time than a nuclear accident release, this may significantly enhance the contamination level (soil and vegetation),
- Deposition velocity can be roughly estimated based on the sedimentation component which depends on the LWC which can be estimated from the visibility Have a better insights on the contribution of fog droplet size distribution on the RN deposition
- Study the turbulence component of the deposition velocity
- Assess the deposition of radionuclides (sink term) based on airborne dust load and airborne activity concentration
- Use of specific sensors to characterize the LWC and fog droplet spectrum size in real-time is better than the integrated visibility HOWEVER the visibility can be sufficient in emergency situation to derive a rough estimate of LWC

- Whatever the fog event, the deposition is higher on every type of vegetation than on bare soil.
- The higher the plant height and the more complex the plant leaf is, the higher the deposition.
- In very windy conditions the precision balance sensitivity may require some adaptations to cope with wind-induced measurement artefacts

Thank you for your attention

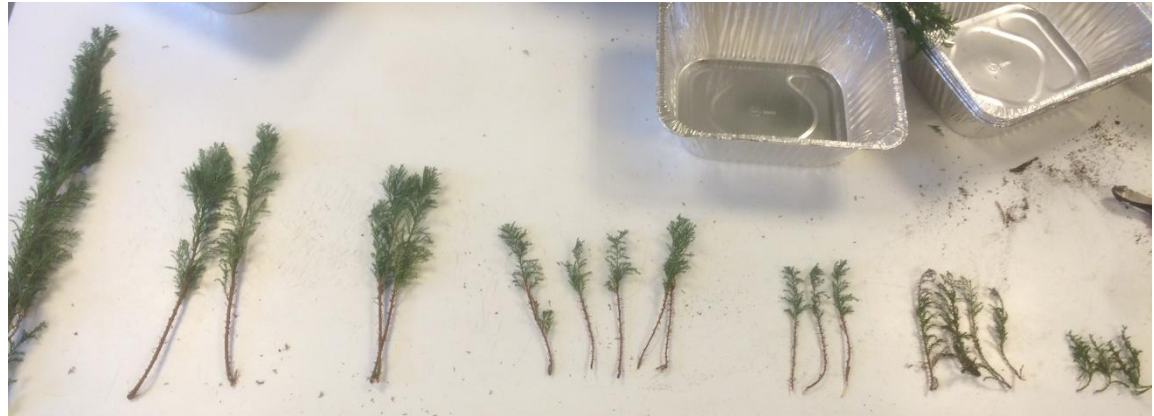




Number of foggy days
in October in France (1961-
1990)

Détermination de la surface foliaire totale à partir de la masse foliaire

➤ Pour 10 individus :



- Constitution de lot en fonction de la taille des branches
 - pour chaque lot, détermination du nombre de sous-branches et du nombre de feuilles ainsi que la surface moyenne d'une feuille
 - pesée de chaque lot avec distinction masse foliaire/masse branches
 - détermination d'une relation surface foliaire/masse foliaire
- Pour le reste des individus:
- Pesée de la masse foliaire et de la masse des branches fraîches et sèches

Instrument	Measured parameter	Measurement frequency
Visibilimeter	Visibility (m)	2 min
Particulate Volume Monitor (PVM-100)	Liquid Water Content, LWC (g m^{-3})	2 min
Fog Monitor 120 (FM-120)	Size distribution of fog droplets	0.1 s
Weather Transmitter (WXT520)	Wind speed (m s^{-1})	2 min
Balance (KA15s)	Mass of container+plants+fogwater (g)	10 to 20 min