

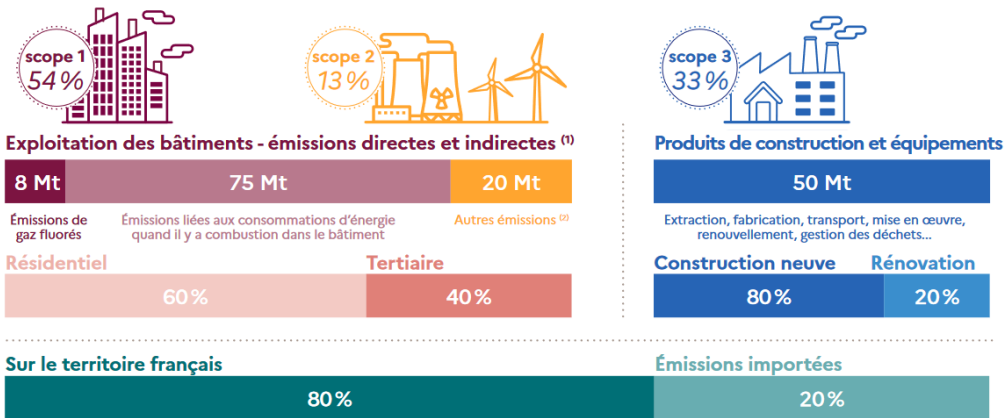
# **Les interactions bois-champignons**

## **- durabilité et soutenabilité des matériaux bois -**

Arnaud Besserer

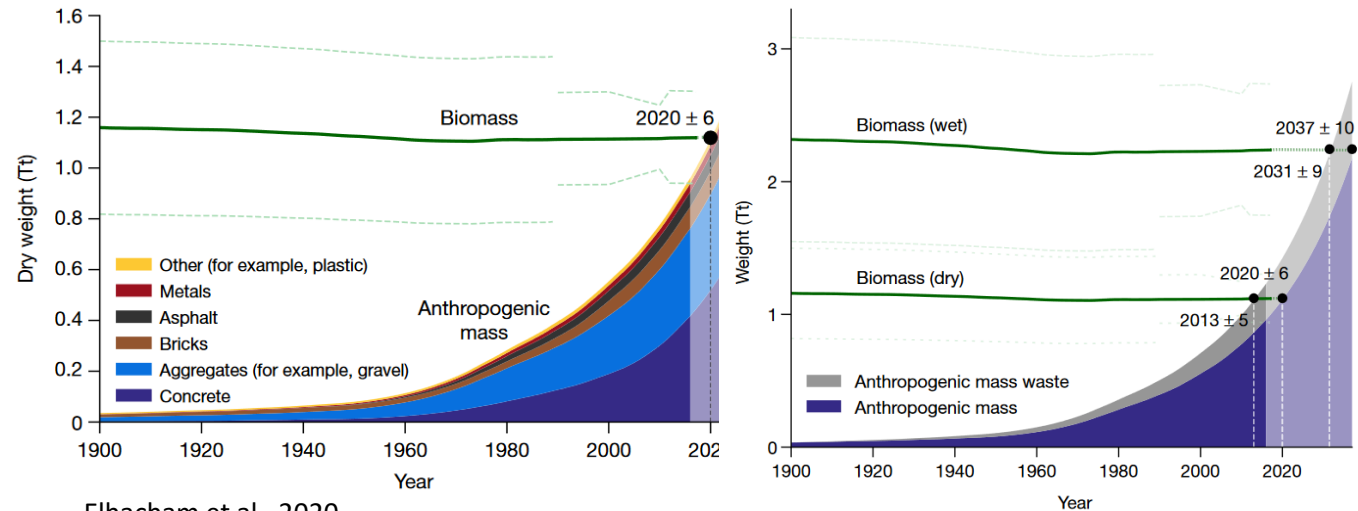


Synthèse du rapport du GIEC (Calvin et al., 2023)

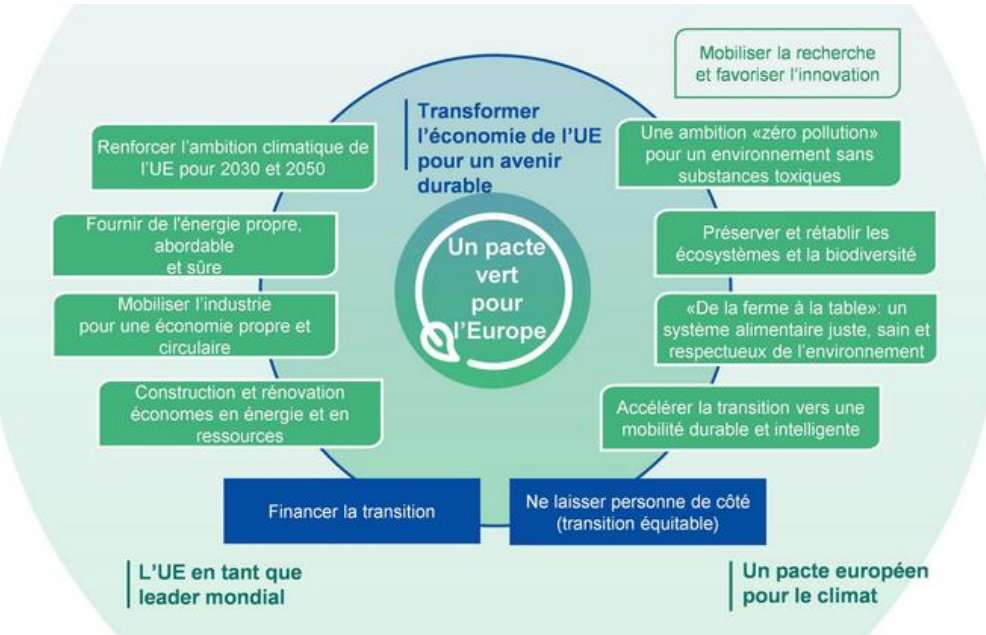


**Bâtiment = 25 % de l'empreinte carbone annuelle de la France**  
 (Feuille de route décarbonation du cycle de vie du bâtiment, 2023)

## La production humaine excède l'ensemble de la biomasse vivante

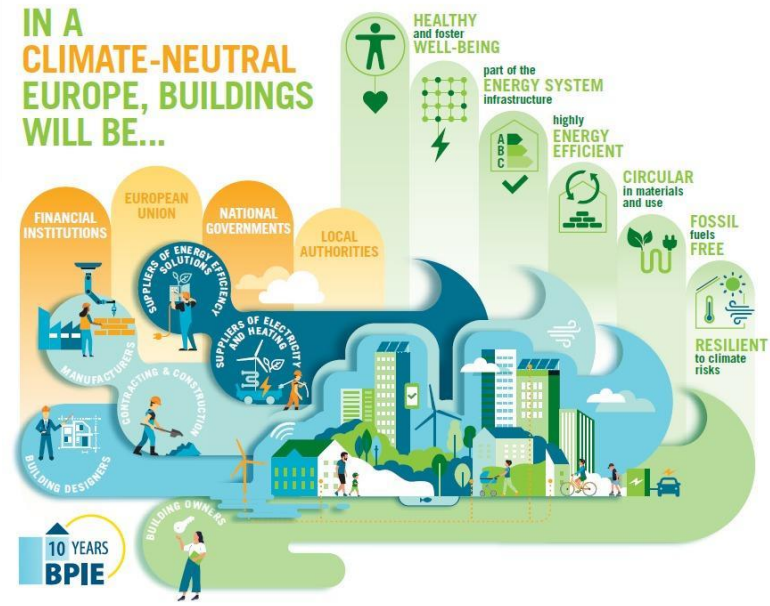


Elhacham et al., 2020  
<https://www.nature.com/articles/s41586-020-3010-5>

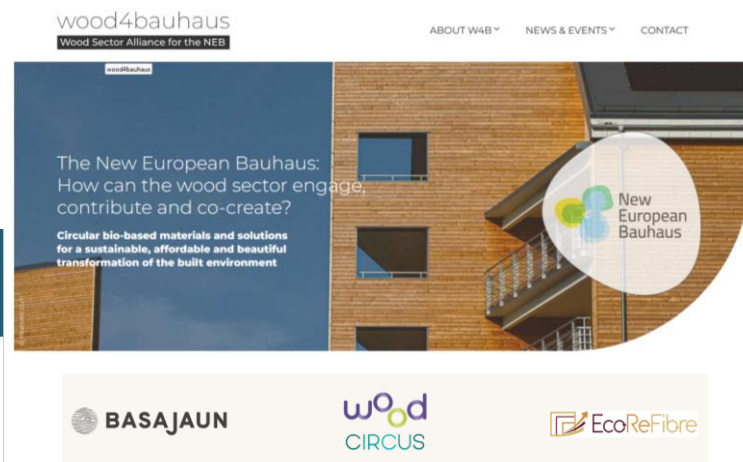


[https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal\\_fr](https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_fr)

## AN ACTION PLAN FOR THE RENOVATION WAVE: COLLECTIVELY ACHIEVING SUSTAINABLE BUILDINGS IN EUROPE



[https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/renovation-wave\\_en](https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/renovation-wave_en)



Wood4Bauhaus = plateforme ouverte pour le partage, la co-création, les compétences et le développement de politiques dans le secteur européen du bois

<https://wood4bauhaus.eu/>

**Bois et terre crue = remplaçants « écologiques » du béton en usage structurel**

# Bois = biodégradable par microorganismes

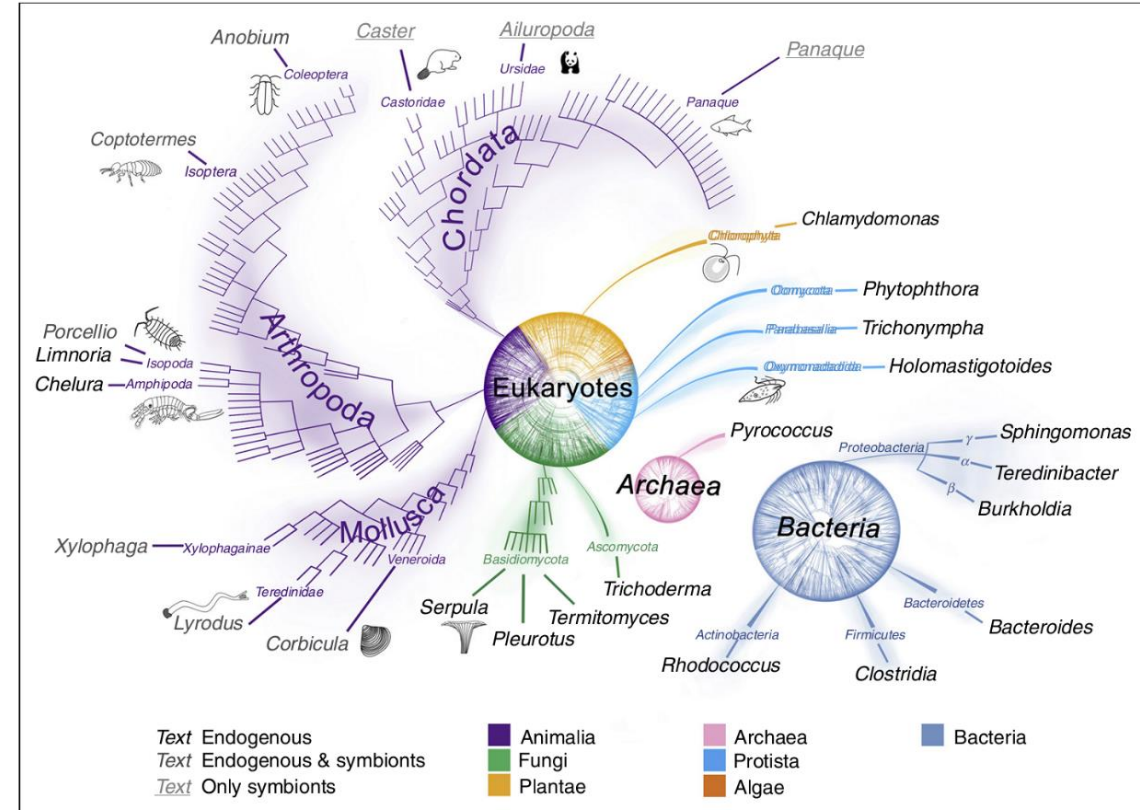
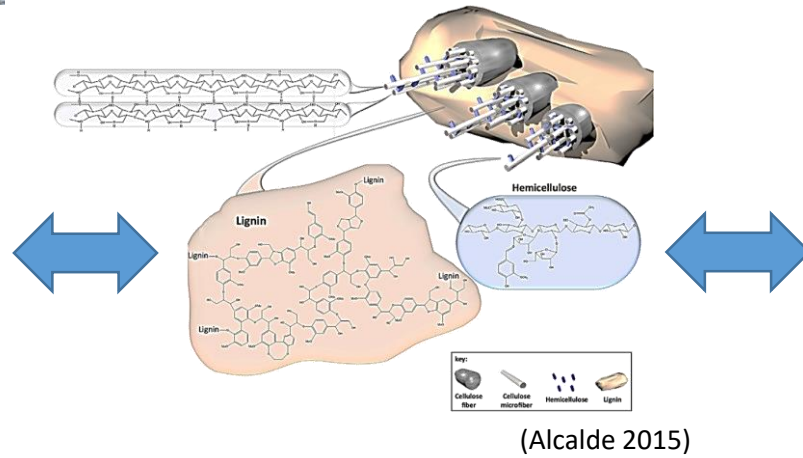
## Dans son environnement naturel



## Dans les bâtiments



<https://www.lanouvellerepublique.fr>



Cragg et al., 2015  
<https://doi-org/10.1016/j.cbpa.2015.10.018>  
 Current Opinion in Chemical Biology

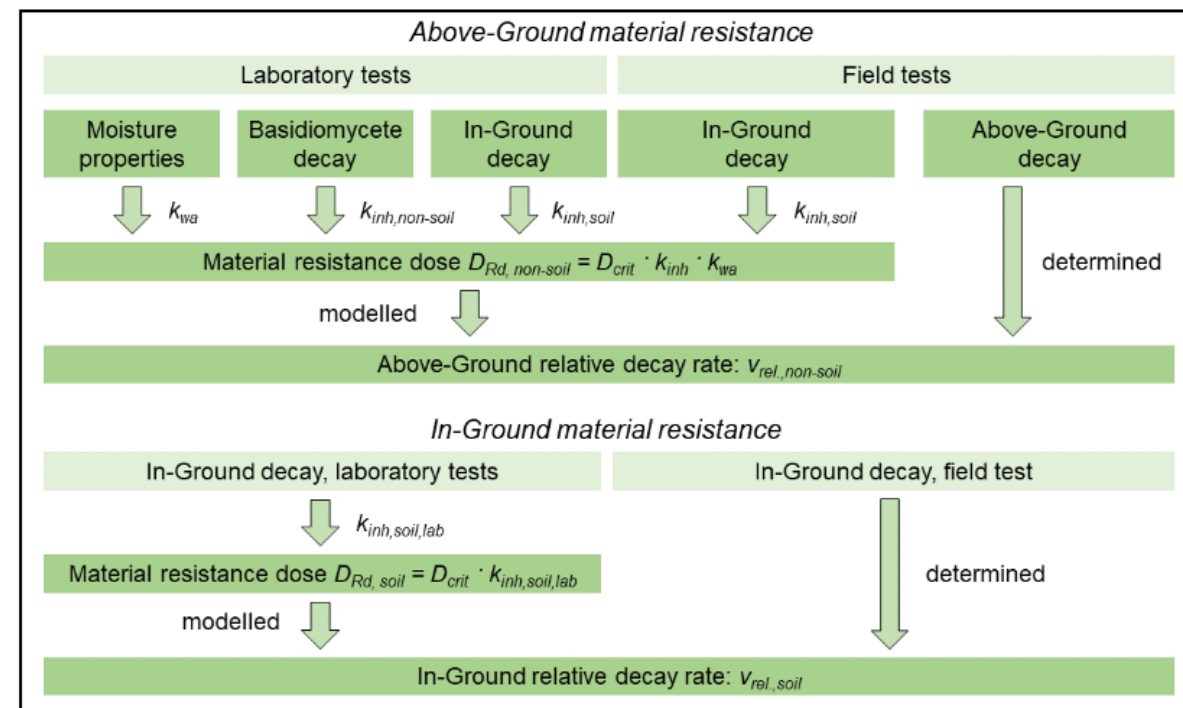
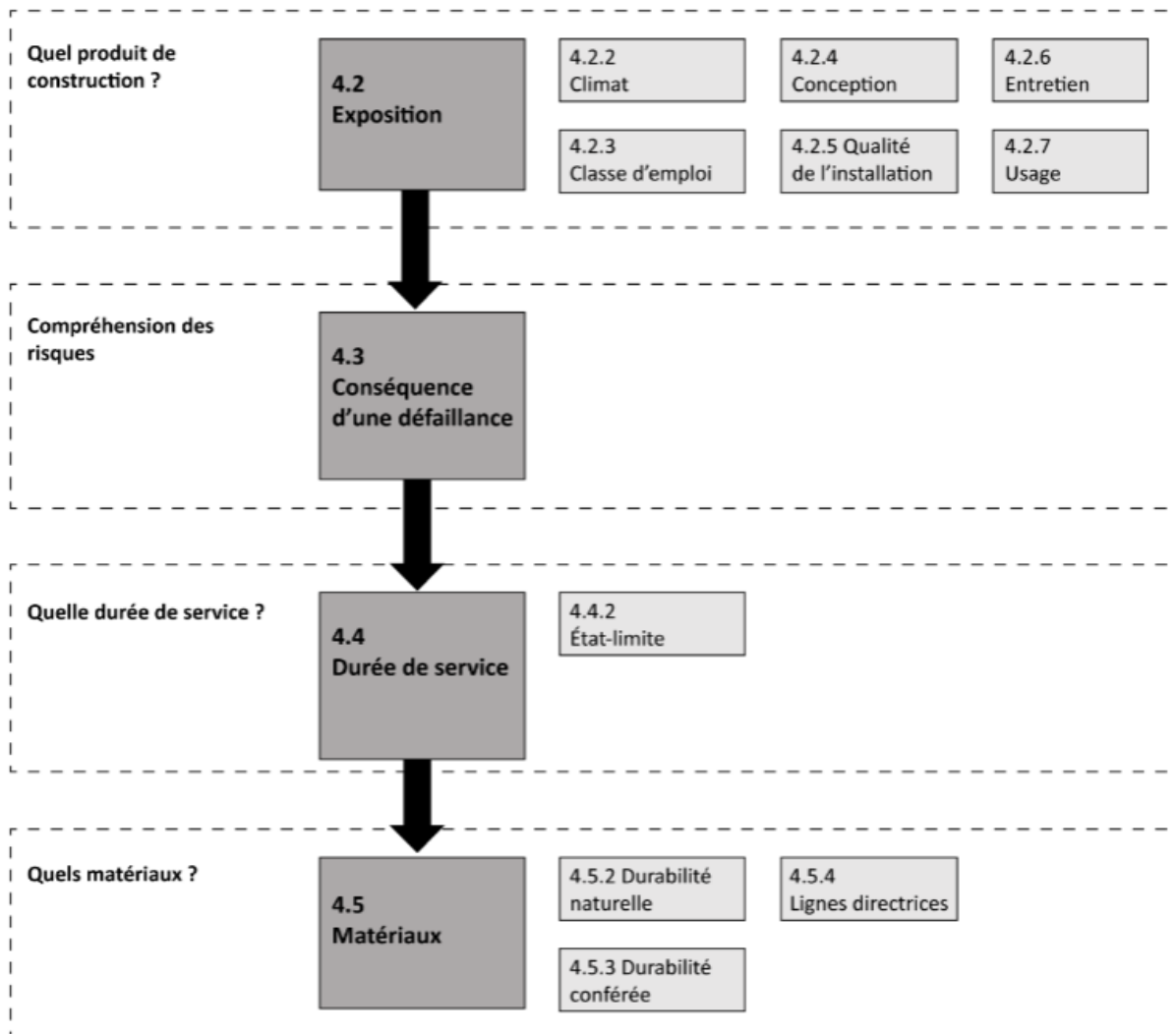
Dégradation de la matière lignocellulosique = caractère commun à de nombreux organismes

➡ Durabilité ?

## Définitions :

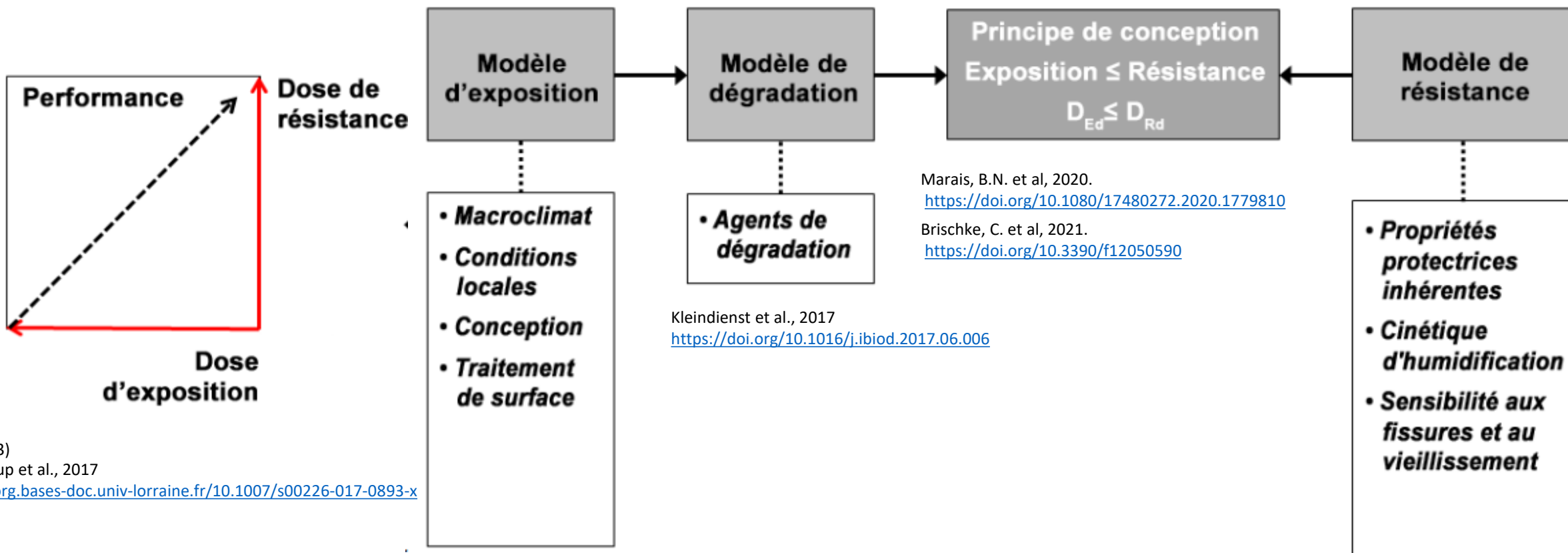
- **Durabilité biologique (naturelle ou conférée)** : résistance intrinsèque d'une essence de bois ou d'un matériau à base de bois aux organismes de dégradation biologique.
  - **Résistance du matériau**: capacité inhérente d'un matériau à résister à un risque biologique, basée sur la combinaison de la durabilité naturelle et/ou conférée et de la cinétique d'humidification du matériau pertinente pour les différents agents biologiques
  - **Durée de service**: période suivant l'installation, au cours de laquelle les parties d'un bâtiment, d'une structure ou d'un composant remplissent ou dépassent les exigences de performance attendue.
  - **Performance**: capacité d'une essence de bois ou d'un matériau à base de bois à résister à la dégradation au fil du temps et à remplir ses fonctions essentielles
- 
- EN460 (2023) Durabilité du bois et des matériaux à base de bois - Guide pour déterminer la performance

# Prévoir la durabilité et la performance en service ?



Brischke et al., 2021  
<https://doi.org/10.3390/f12050590>

# Relation exposition-performance-résistance



Marais, B.N. et al, 2020.  
<https://doi.org/10.1080/17480272.2020.1779810>  
 Brischke, C. et al, 2021.  
<https://doi.org/10.3390/f12050590>

Kleindienst et al., 2017  
<https://doi.org/10.1016/j.ibiod.2017.06.006>

EN 460 (2023)  
 Meyer-Veltrup et al., 2017  
<https://doi-org.bases-doc.univ-lorraine.fr/10.1007/s00226-017-0893-x>

FD P20-651 (2011)  
 Brischke et al., 2013  
<http://www.tandfonline.com/doi/full/10.1179/2042645312Y.0000000014>  
 Niekerk et al., 2022  
<https://doi.org/10.1515/hf-2021-0169>

Brischke, C. et al, 2023  
<https://doi.org/10.1080/17480272.2022.2104134>

Variabilité élevée pour chacun des facteurs → Modélisation des performances très complexe (modèle de Meyer-Veltrup)  
 Forte relation teneur en eau <-> risque de dégradation

# Cartographie des doses d'exposition en Europe

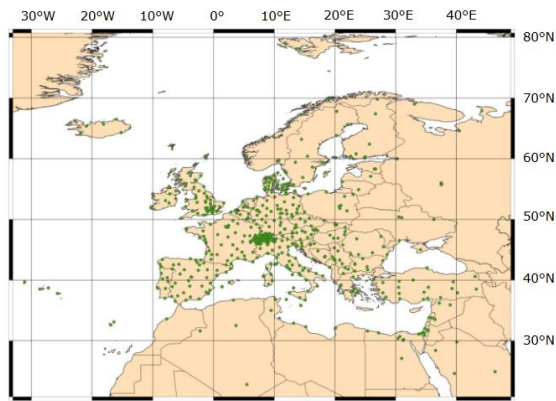
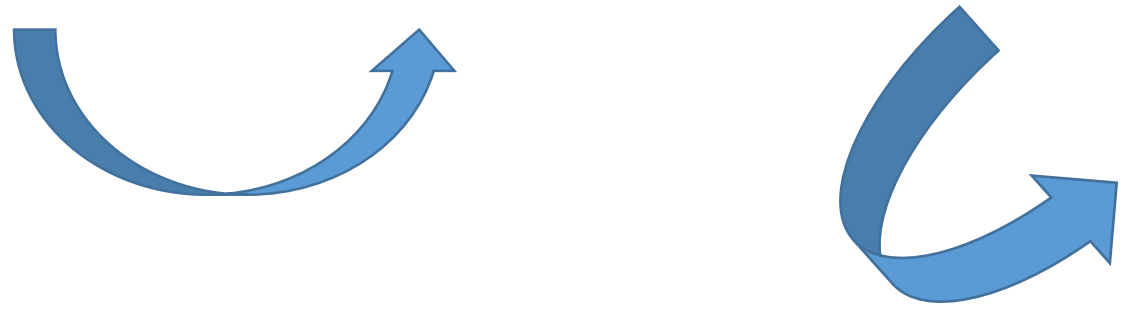
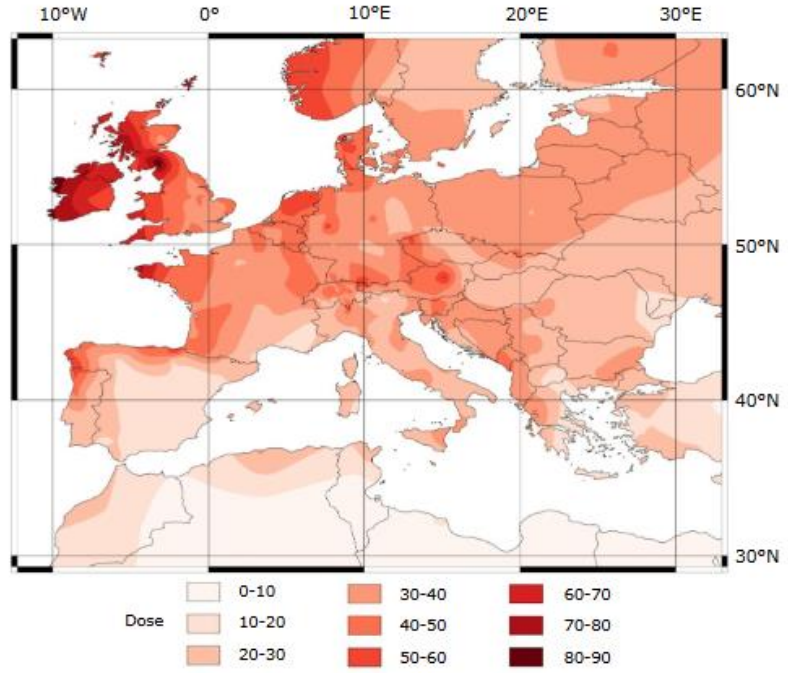
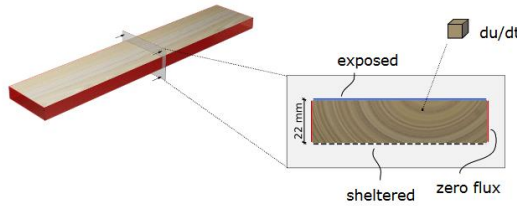
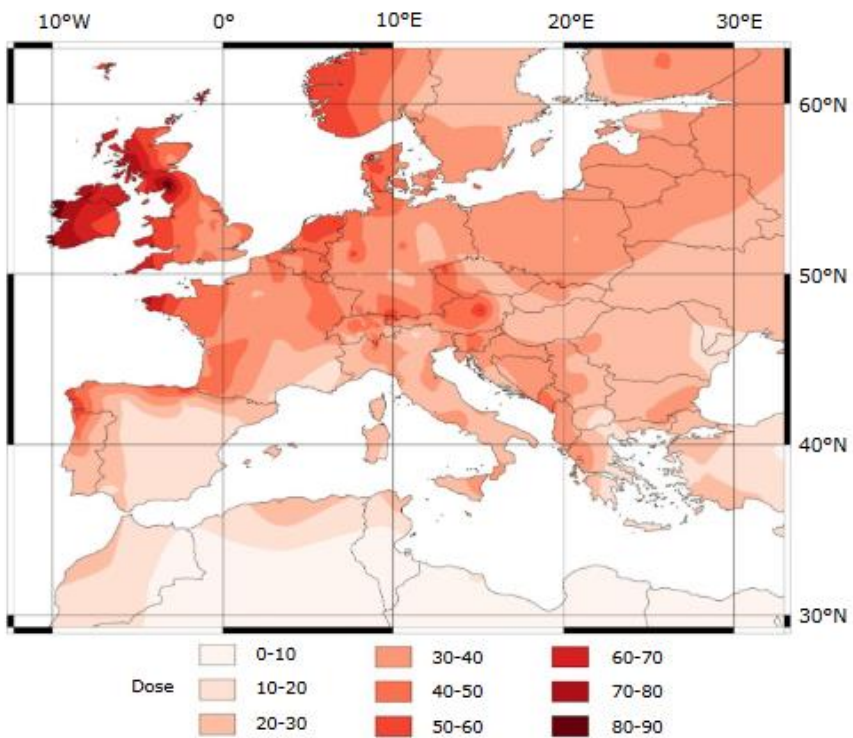


Figure 2: Locations selected for meteorological variable extraction and mapping.

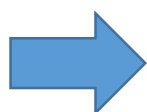


Dose (days per year)	SL of a <i>Picea abies</i> reference board (years)	Minimum $d_{rd,rel}$ required to reach 100 year SL	Examples of wooden material that meets minimum requirements
10	22.91	4.36	<b>Untreated wood species:</b> Kiri ( <i>Paulownia</i> spp.); European larch ( <i>Larix decidua</i> ); Douglas fir ( <i>Pseudotsuga menziesii</i> ); Western red cedar ( <i>Thuja plicata</i> ). <b>Treated timbers:</b> <i>Picea abies</i> ~Cu (II) sulph. low / high; <i>P. abies</i> ~CuEA low / high; <i>P. abies</i> ~CuEAOA low / high; <i>P. abies</i> ~CuEAOAQuat low; <i>P. abies</i> ~BorEAOAQuat low / high; <i>P. abies</i> ~Cu 0.25 %, dip. 8-h / dip. 24-h / vac. + press.; <i>P. abies</i> ~Cu 0.5 %, dip. 8-h / 24-h / vac. / vac. + press.; <i>Pinus sylvestris</i> ~Cu 0.25 %, dip. 24-h; <i>P. sylvestris</i> ~metal-free organic.
20	11.46	8.73	<b>Untreated wood species:</b> Sweet chestnut ( <i>Castanea sativa</i> ); Honey locust ( <i>Gleditsia triacanthos</i> ); European oak ( <i>Quercus robur</i> / <i>Q. petraea</i> ); Juniper ( <i>Juniperus communis</i> ). <b>Modified timbers:</b> <i>P. sylvestris</i> ~TM; <i>Acer platanoides</i> ~FA; <i>P. sylvestris</i> ~DMDHEU, 20% WPG. <b>Treated timbers:</b> <i>P. abies</i> ~BorEAOAQuat high; <i>P. abies</i> ~Cu 0.25 %, vac. / dip. 8-h; <i>P. sylvestris</i> ~Cu 0.25 %, vac. + press.; <i>P. sylvestris</i> ~Cu 0.5 %, dip. 8-h / 24-h; <i>P. sylvestris</i> ~Cu 0.5 %, vac. / vac. + press.; <i>P. sylvestris</i> ~CCA, 9 kg/m <sup>3</sup>
30	7.64	13.09	<b>Untreated wood species:</b> Basralocus ( <i>Dicorynia guianensis</i> ); Black locust ( <i>Robinia pseudoacacia</i> ); Bongossi ( <i>Lophira alata</i> ); Yew ( <i>Taxus baccata</i> ). <b>Modified timbers:</b> <i>Fagus sylvatica</i> ~TM, <i>Pinus</i> spp. sw (Southern pine)~FA. <b>Treated timbers:</b> <i>P. sylvestris</i> ~CCA, 2 kg/m <sup>3</sup> / 4 kg/m <sup>3</sup> ; <i>P. sylvestris</i> ~Cu 0.25 %, vac.; <i>L. decidua</i> ~Cu 0.5 %, dip. 24-h / vac. + press.
40	5.73	17.46	<b>Untreated wood species:</b> Amaranth ( <i>Peltogyne</i> spp.); Teak ( <i>Tectona grandis</i> ). <b>Modified timbers:</b> <i>P. abies</i> ~OHT; <i>P. abies</i> ~TM <b>Treated timbers:</b> <i>L. decidua</i> ~Cu 0.25 %, vac. + press.
50	4.58	21.82	<b>Modified timbers:</b> <i>Fraxinus excelsior</i> ~OHT; <i>Pinus</i> ssp. sw (Southern pine)~AC; <i>P. sylvestris</i> sw~FA.
60	3.82	26.18	<b>Treated timbers:</b> <i>L. decidua</i> ~Cu 0.25 %, dip. 24-h
70	3.27	30.55	<b>Natural wood species:</b> Merbau ( <i>Intsia bijuga</i> ). <b>Modified timbers:</b> <i>P. sylvestris</i> / <i>P. radiata</i> sw~AC
100	2.29	43.64	<b>Treated timbers:</b> <i>L. decidua</i> ~Cu 0.5 %, vac.

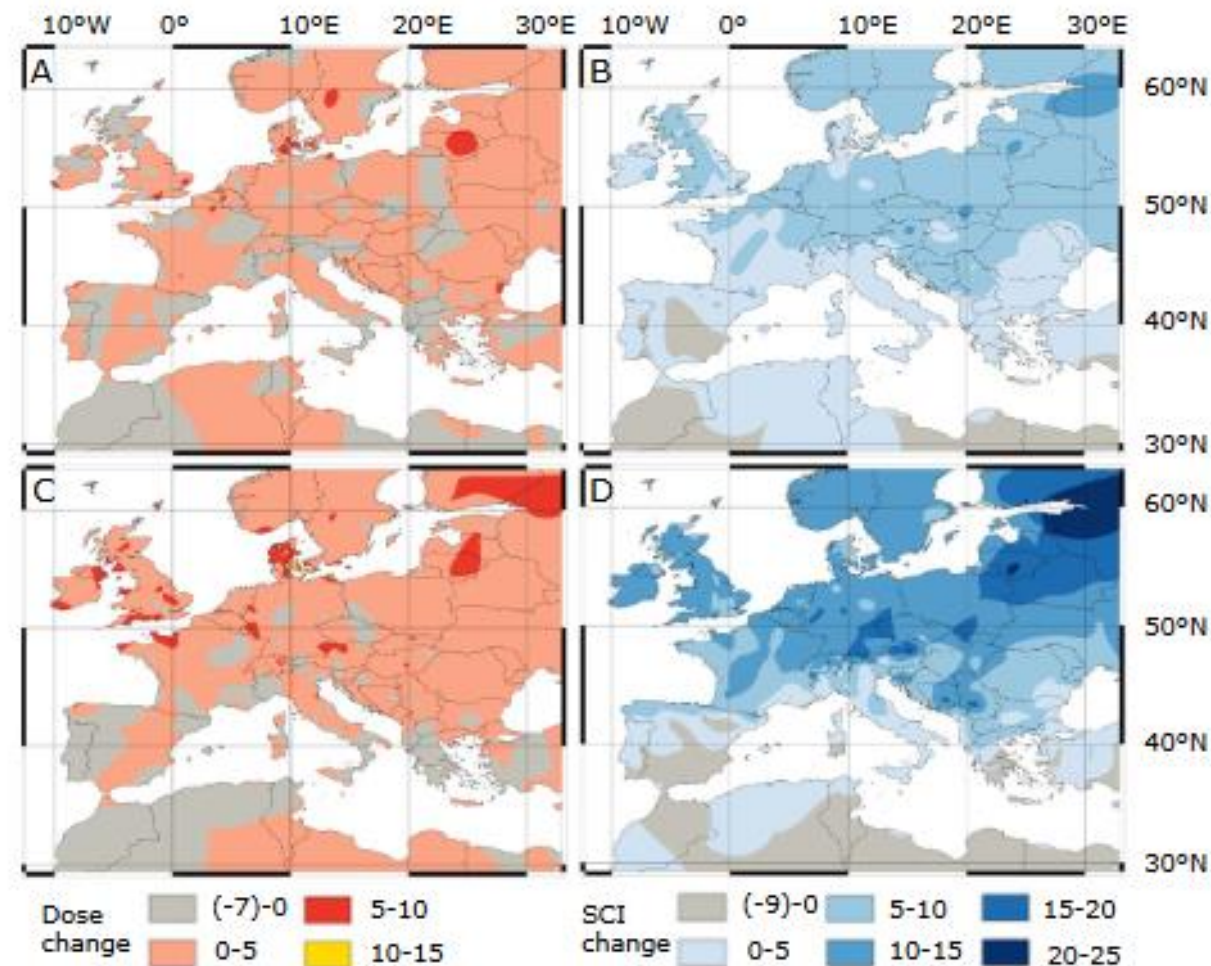




RCP 2.6  
(+ 1,5°C en 2100)

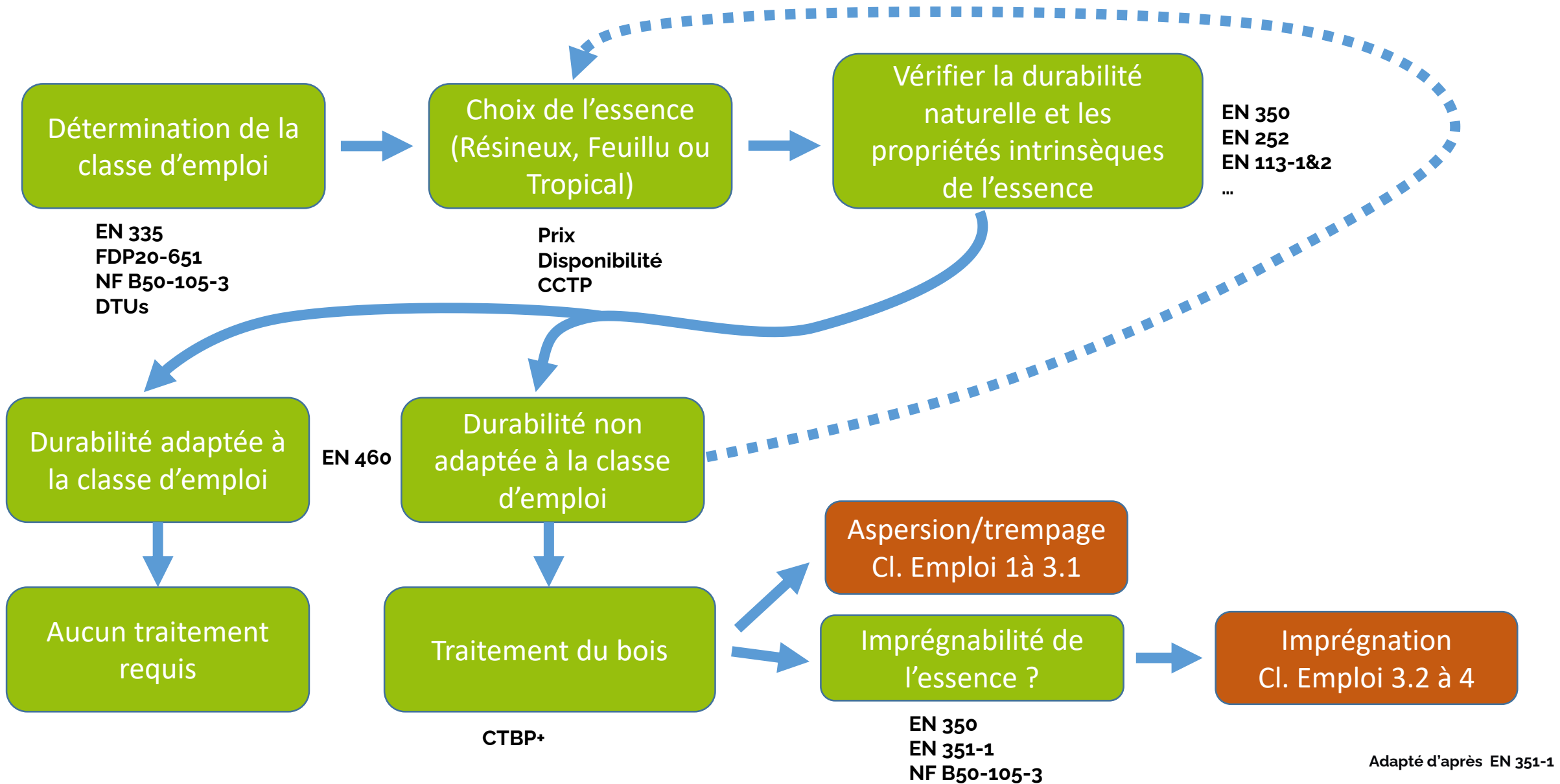


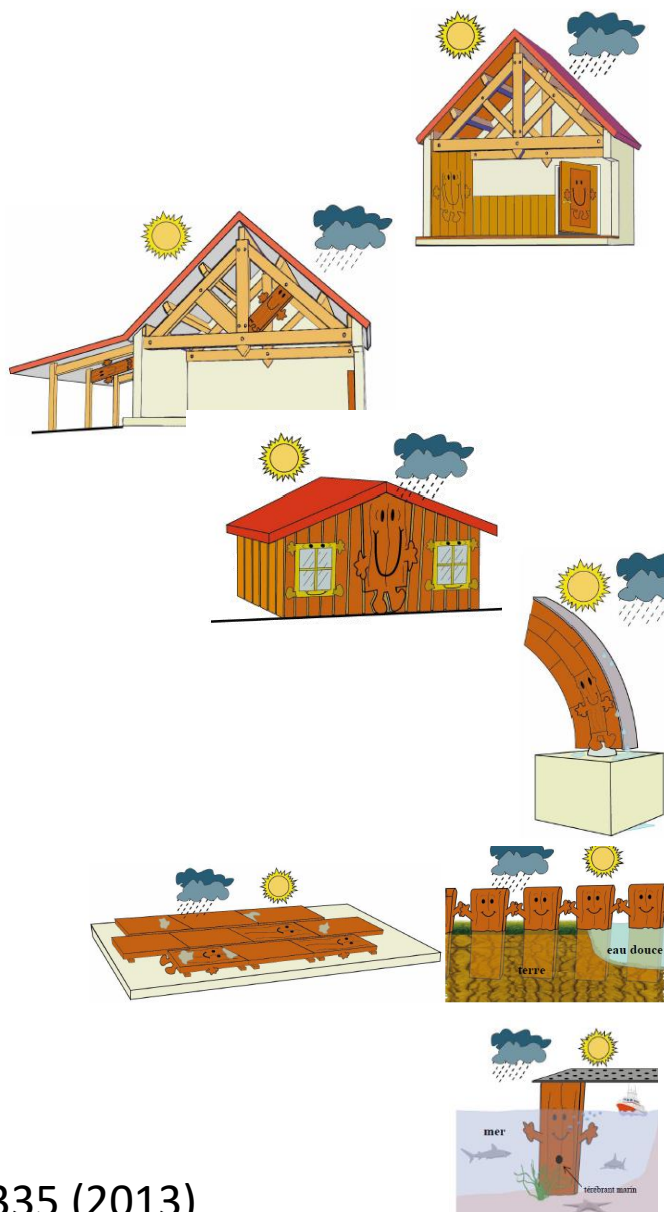
RCP 8.5  
(+ 4,6°C en 2100)



Niekerk et al., 2022  
<https://doi.org/10.1515/hf-2021-0169>

Changements climatiques →  pression de dégradation sur les constructions réalisées aujourd'hui

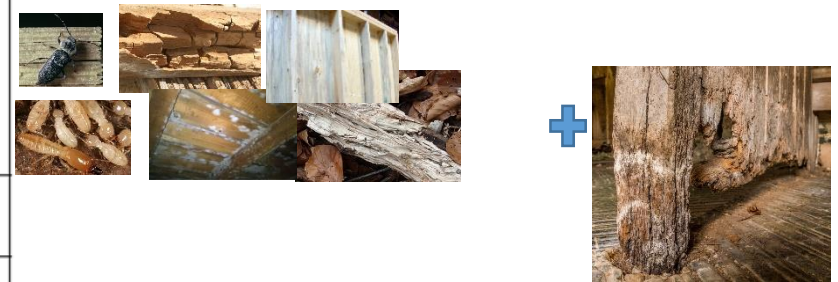
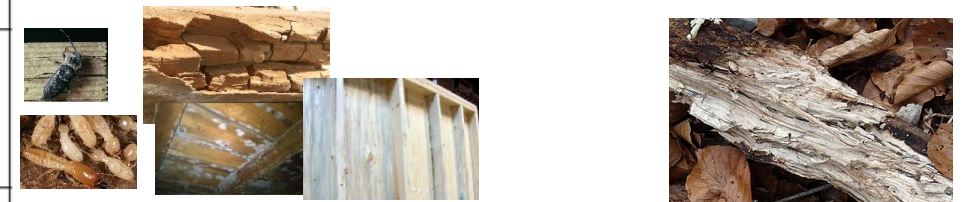




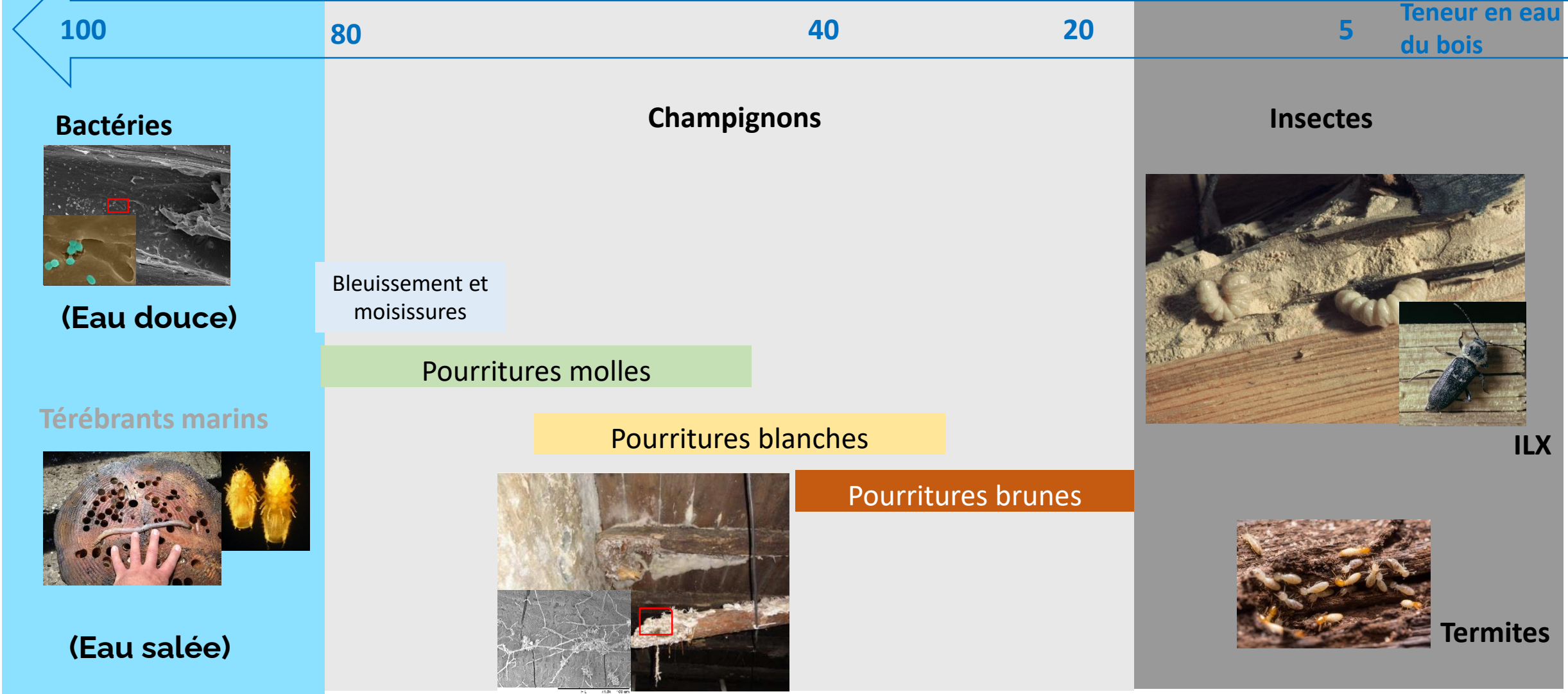
Classe d'emploi	Usage général <sup>a</sup>	Occurrence des agents biologiques <sup>b, c</sup>				
		Champignons de discoloration	Champignons lignivores	Coléoptères	Termites	Térébrants marins
1	À l'intérieur, au sec	-	-	U	L	-
2	À l'intérieur, ou sous abri, non exposé aux intempéries. Possibilité de condensation d'eau	U	U	U	L	-
3	À l'extérieur, au-dessus du sol, exposé aux intempéries  Si subdivisée : 3.1 Conditions d'humidification courtes 3.2 Conditions d'humidification prolongées	U	U	U	L	-
4	À l'extérieur en contact avec le sol et/ou l'eau douce	U	U	U	L	-
5	Immergé dans l'eau salée de manière régulière ou permanente	U <sup>d</sup>	U <sup>d</sup>	U <sup>d</sup>	L <sup>d</sup>	U

# Classe d'emploi et risques biologiques associés

Classe d'emploi	Insectes	Champignons
1  <u>DOM : Classe d'emploi non pertinente</u>	<b>France métropolitaine :</b> — Cérambycidés (G) — Anoblidés (G)  — Lyctidés : (G) — Termites souterrains (R) — Termites de bois sec (R)	/
2	<b>France métropolitaine :</b> Comme en classe 1 <b>DOM :</b> — Cérambycidés (G) — Lyctidés (G) — Bostryches (G) — Termites de bois sec (G) — Termites souterrains (G) — Termites arboricoles(R)	— pourriture cubique <sup>b</sup> (G) — bleuissement (G) <sup>a</sup> — moisissures (G) <sup>a</sup>
3	Comme en classe 2	— pourriture cubique (G) — pourriture fibreuse (G) — bleuissement (G) <sup>a</sup> — moisissures (G) <sup>a</sup>
4	Comme en classe 2	— pourriture cubique (G) — pourriture fibreuse (G) — pourriture molle (G) — bleuissement (G) <sup>a</sup> — moisissures (G) <sup>a</sup>
5	<b>Insectes et champignons :</b> idem classe 4. <b>Térébrants marins</b> (Tarets, Pholades, Limnaires) (G)	
<sup>a</sup> des mesures spécifiques s'imposent si une protection contre ces agents est requise par le maître d'ouvrage sur conseil de son maître d'œuvre. <sup>b</sup> l'occurrence et le développement des pourritures cubiques sont moins fréquentes en classe 2 qu'en classe 3. (G) : présence générale (R) : présence régionale		



NF B 50-105-3  
(2014)



100

80

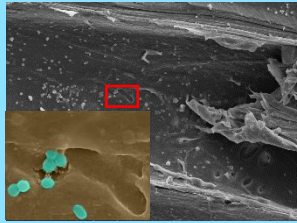
40

20

5

Teneur en eau du bois

**Bactéries**



(Eau douce)

Térébrants marins



(Eau salée)

**Champignons**

Bleuissement et moisissures

Pourritures molles

Pourritures blanches

Pourritures brunes



**Insectes**



ILX



Termites

## Lignicoles



80-100%

Vivent dans ou sur le bois **mais** n'altèrent pas la structure

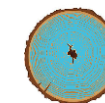
### Bleuissement



### Moisissures



## Lignivores

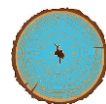


20-80%

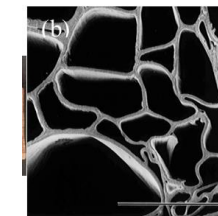
Vivent dans le bois **et** altèrent la structure

### Pourritures

#### Brunes



20-40%



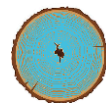
#### Blanches



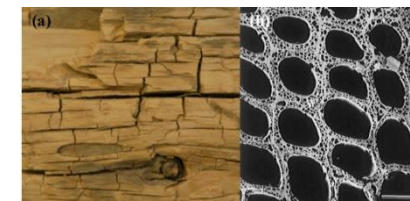
40-60%



#### Molles



60-80%



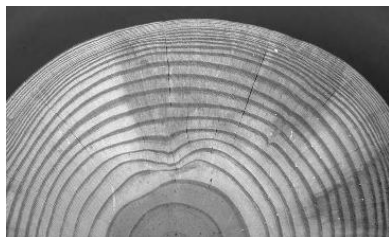
## Lignicoles



80-100%

Vivent dans ou sur le bois mais n'altèrent pas la structure

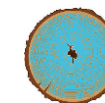
### Bleuissement



### Moisissures



## Lignivores

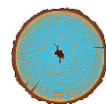


20-80%

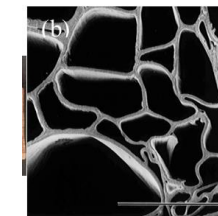
Vivent dans le bois **et** altèrent la structure

### Pourritures

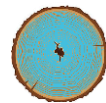
#### Brunes



20-40%



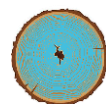
#### Blanches



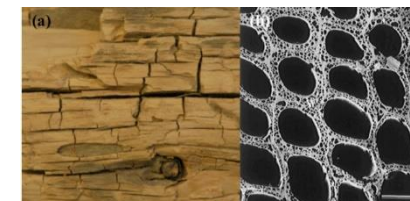
40-60%



#### Molles



60-80%



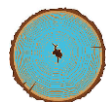
Brunes



20-40%



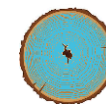
Blanches



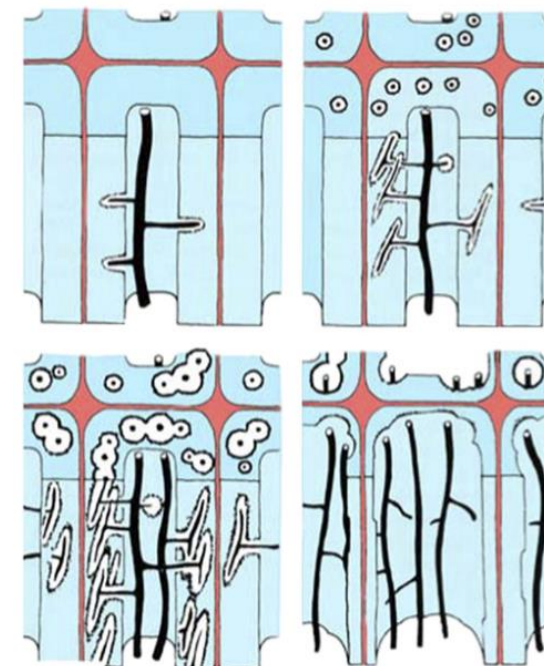
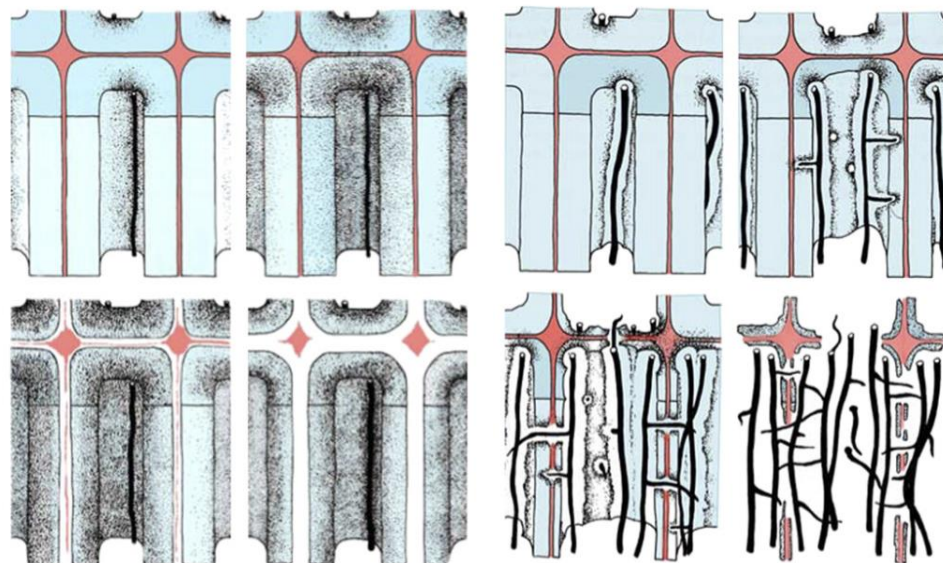
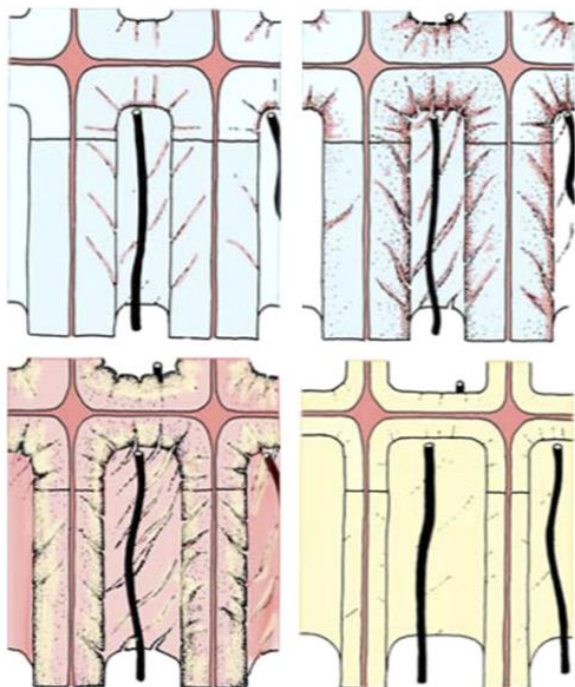
40-60%



Molles



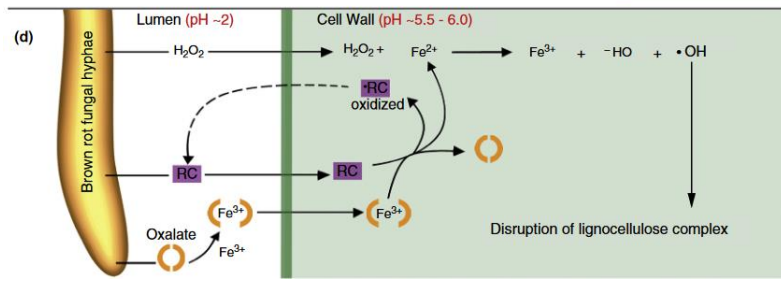
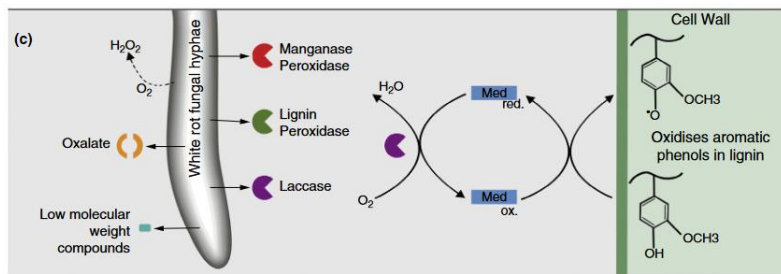
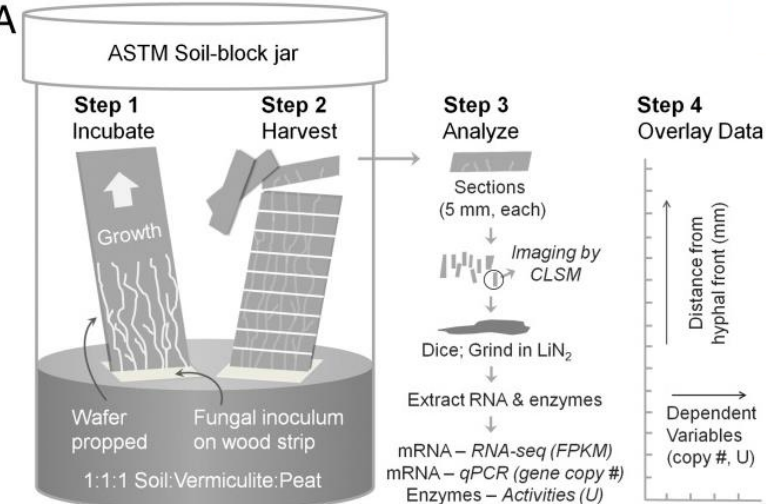
60-80%



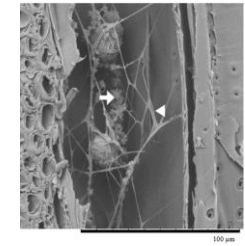


# La dégradation des constituants pariétaux

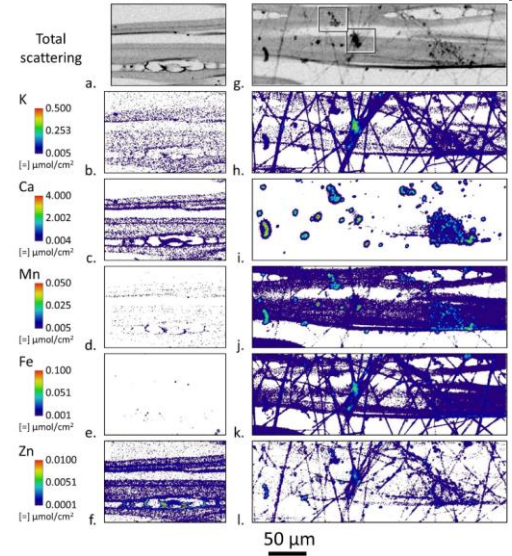
Control two- $\mu$ m-thick longitudinal section of wood  
Two- $\mu$ m-thick longitudinal section of wood exposed to *Serpula lacrymans*



Cragg et al., 2015  
<https://doi-org/10.1016/j.cbpa.2015.10.018>

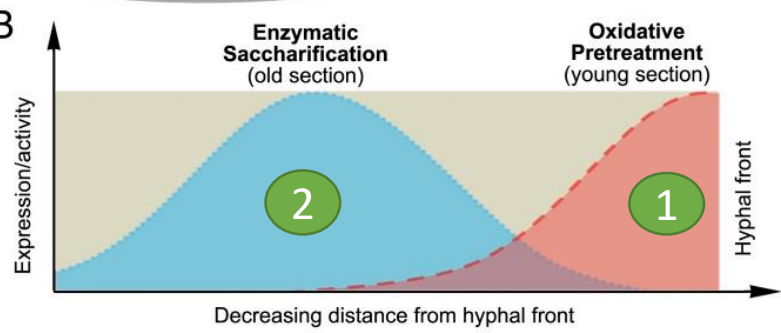


Kleindienst et al., 2017  
<https://doi-org/10.1016/j.ibiod.2017.06.006>

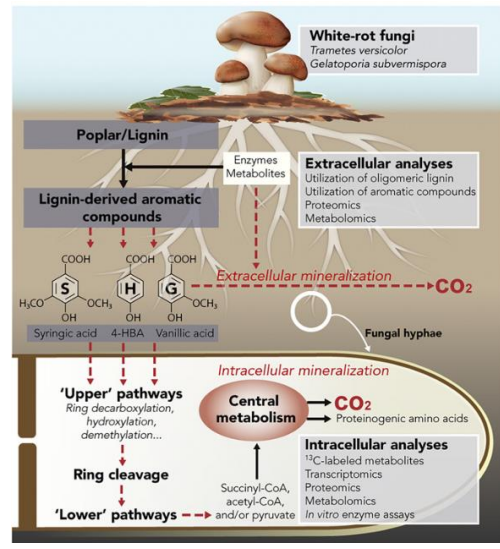
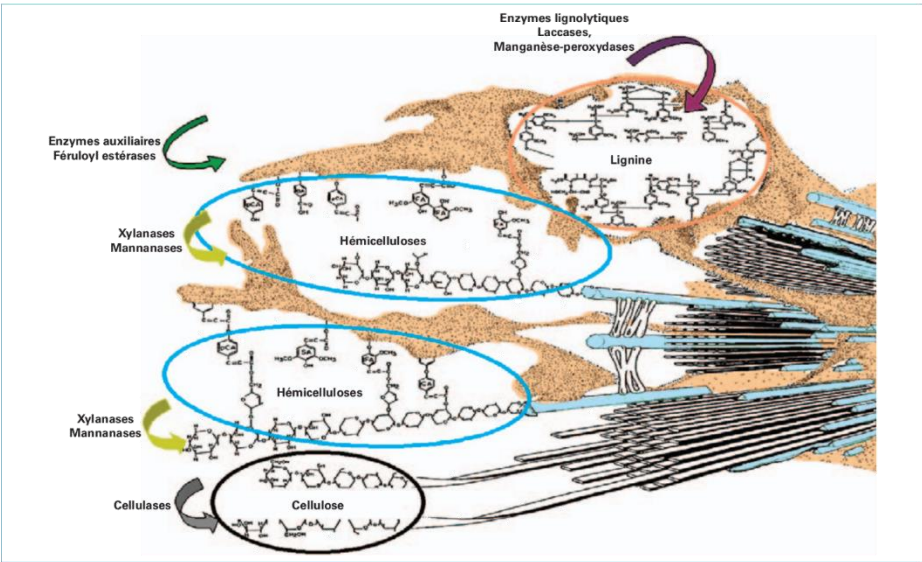


Kirker et al., 2017  
<https://doi-org/10.1038/srep41798>

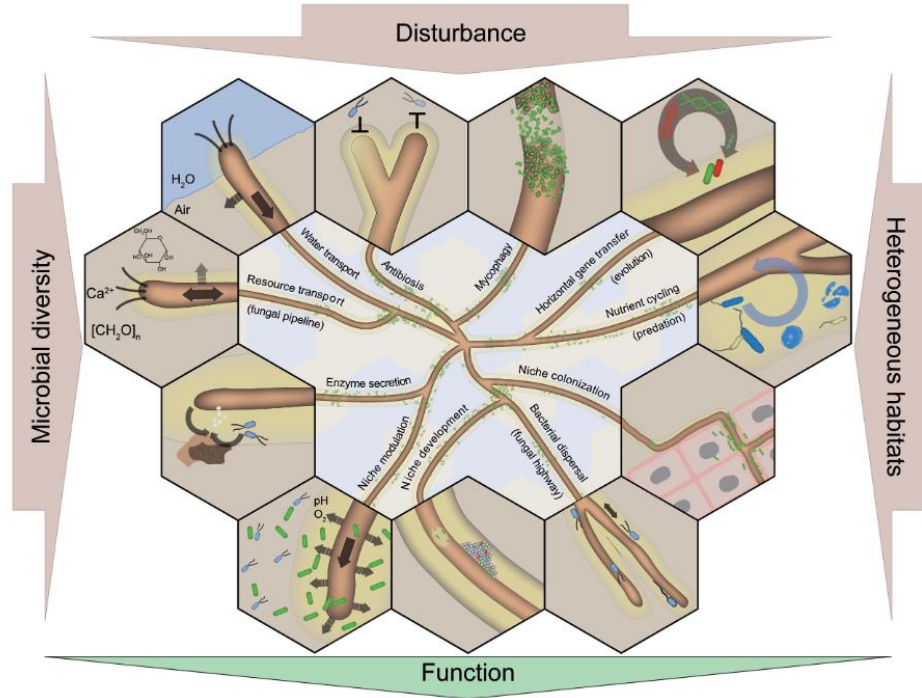
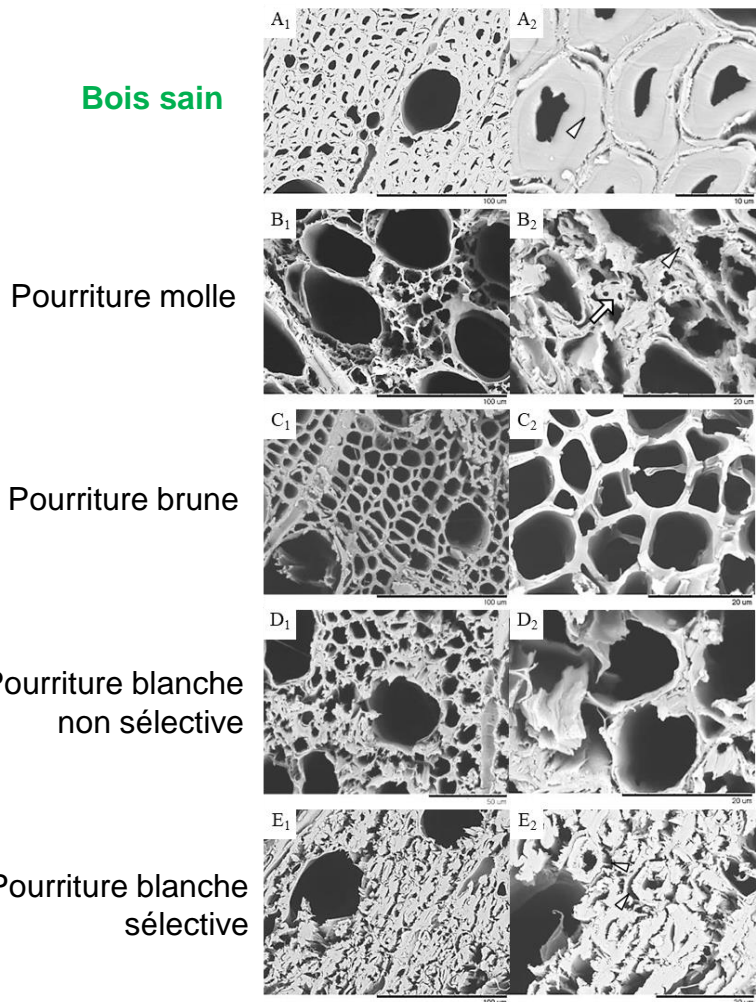
Zelinka et al., 2019  
<https://doi-full/10.1080/17480272.2018.1458049>



Presley et Schilling, 2017  
<http://aem.asm.org/lookup/doi/10.1128/AEM.02987-16>

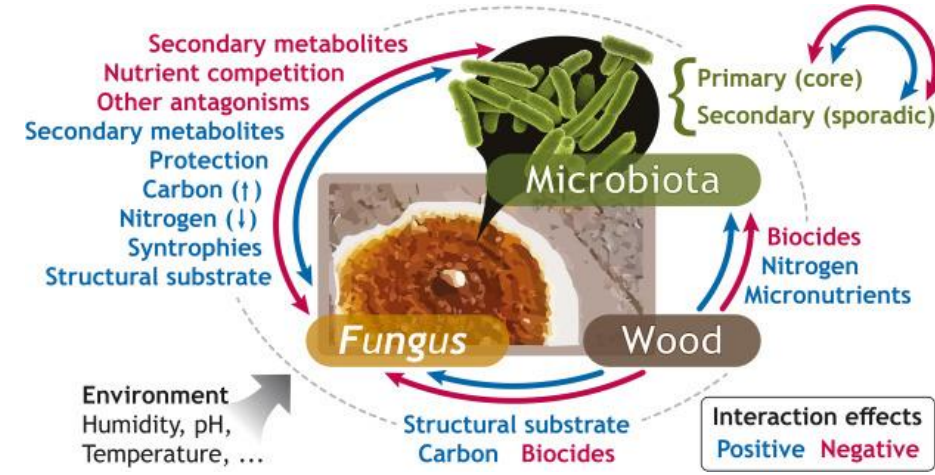


Del Cerro et al., 2021  
<https://doi.org/10.1073/pnas.2017381118>



Deveau et al., 2018  
<https://doi.org/10.1093/femsre/fuy008>

Bois = holobionte ?



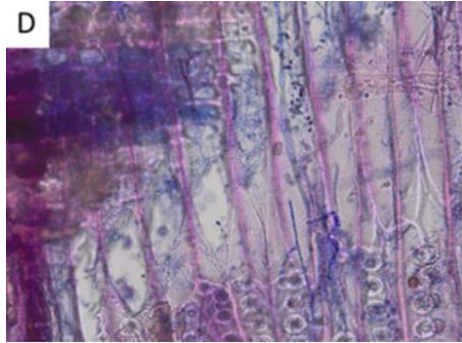
Embacher et al., 2023  
<https://doi.org/10.1016/j.fbr.2022.100305>

## Bacteria

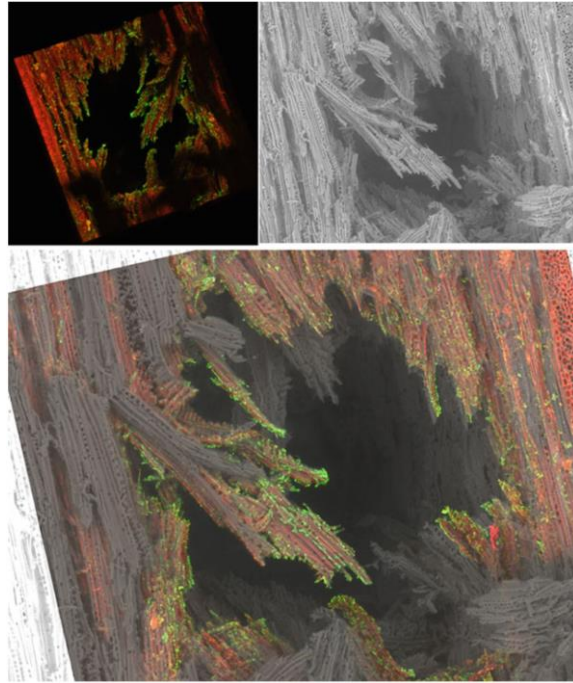


Kleindienst et al., 2017  
<https://doi.org/10.1016/j.ibiod.2017.06.006>

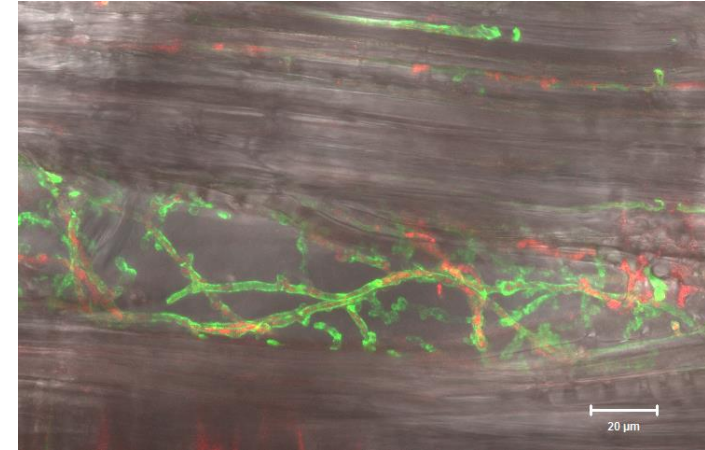
## Microscopie optique



## CLEM

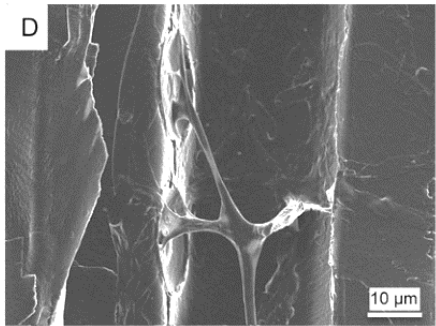


## FISH

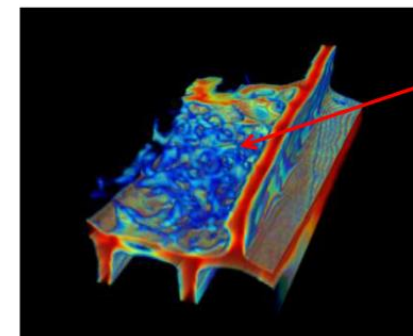


**Green** : WGA- Alexa 488= fungal cell wall  
**Red** : EnUni-1-Alexa 633= biologically active part  
 Transmitted light: beech wood

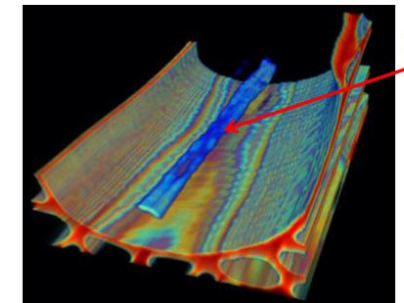
## FEG



## Synchrotron X-ray micro-tomography



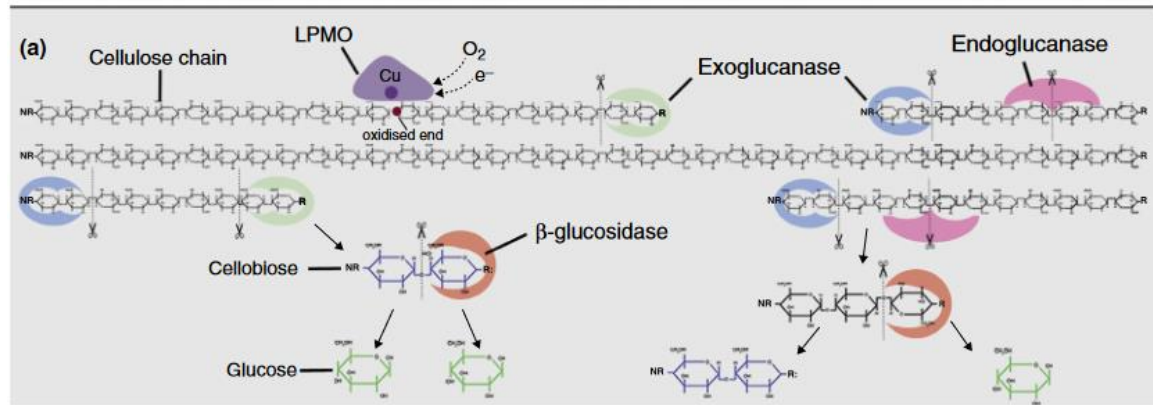
Physisporinus vitreus



Xylaria longipes

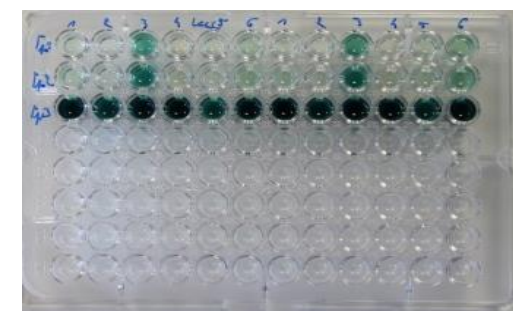
Besserer et al., 2023  
[https://doi.org/10.1007/978-1-0716-2871-3\\_17](https://doi.org/10.1007/978-1-0716-2871-3_17)

Sedighi Gilani et al., 2014  
<http://dx.doi.org/10.1016/j.jsb.2014.06.003>



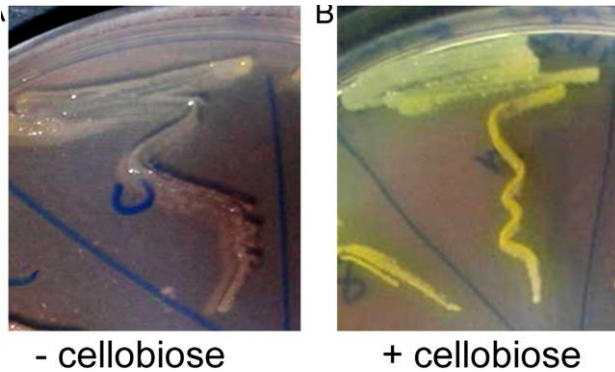
Extraction

## Activités enzymatiques



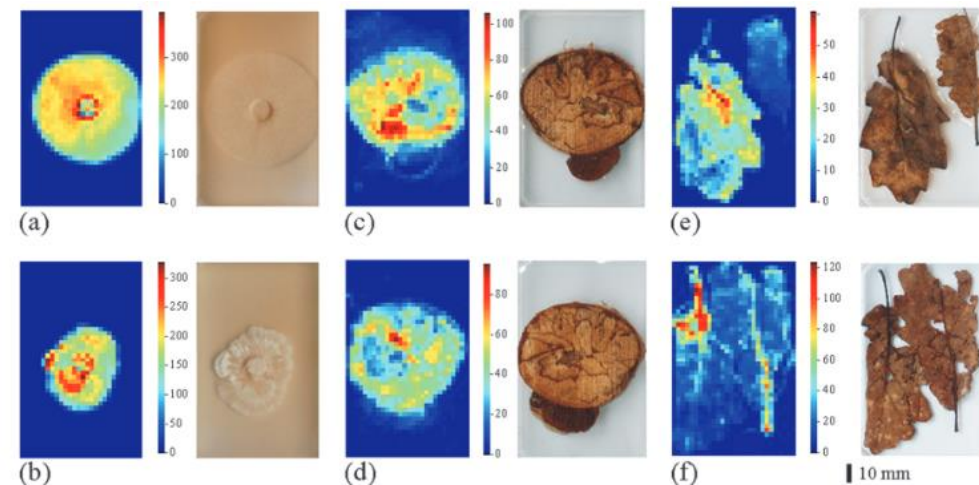
Prédiction de la dégradation

## Génération de biosenseurs biologiques

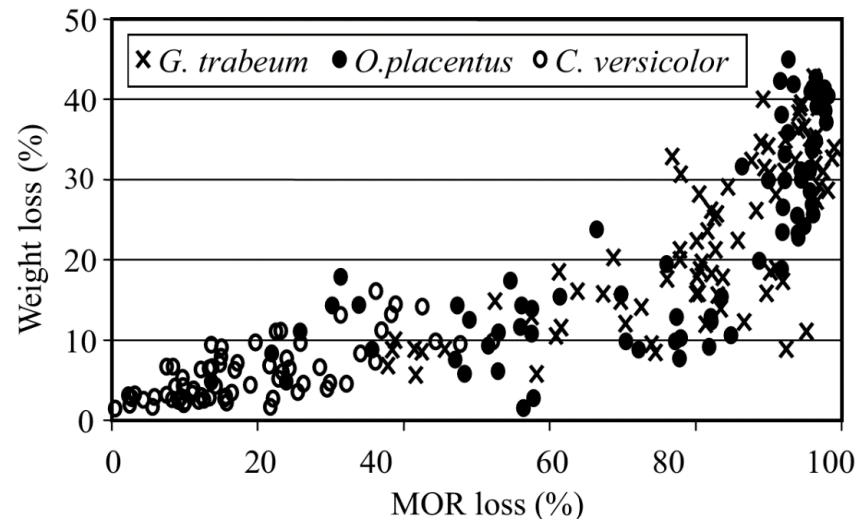
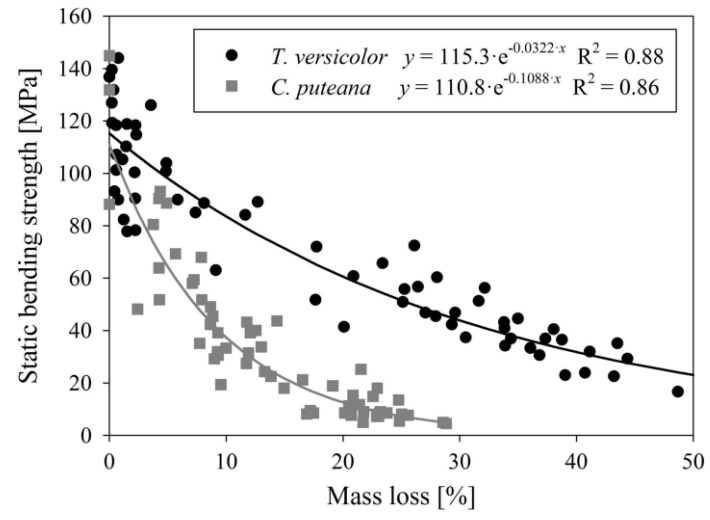
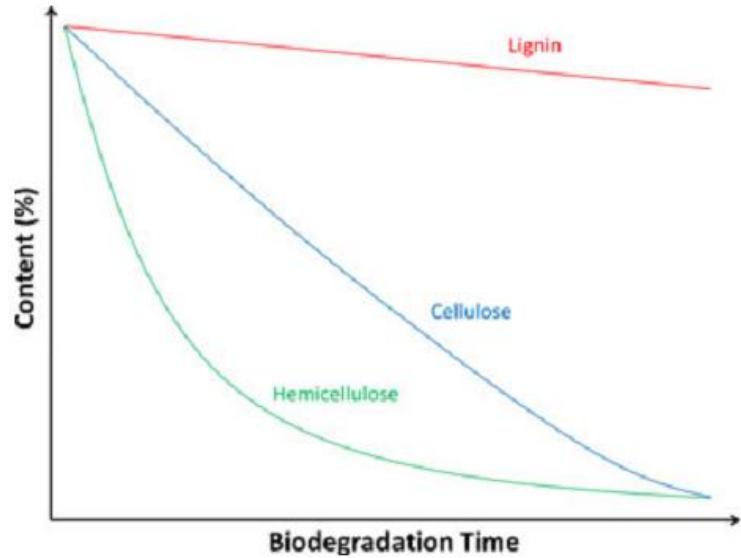


Toussaint et al. 2016  
<https://doi-org/10.1016/j.jbiotec.2016.10.003>

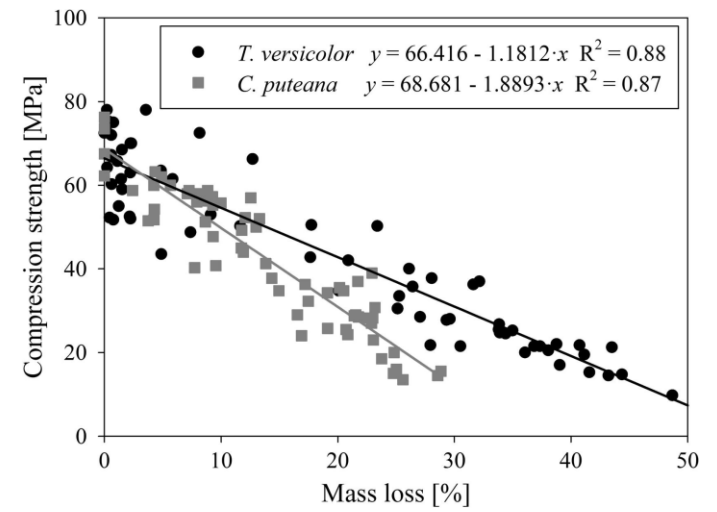
## Cartographie des activités enzymatiques



Baldrian and Vetrovsky, 2012  
<https://doi.org/10.1128/AEM.07953-11>

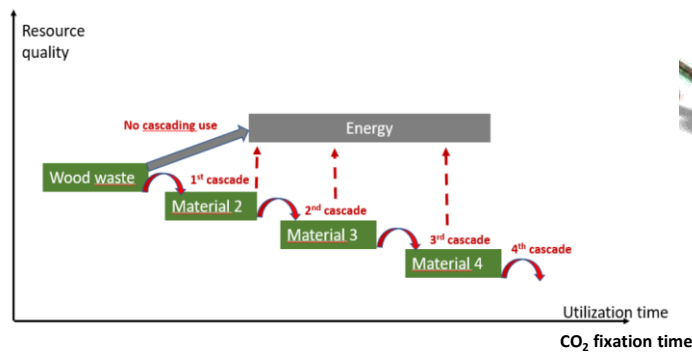


Curling et al., 2002



(Witomski et al., 2016)

# Les interactions bois-champignon dans le recyclage du bois



Besserer et al., 2021  
<https://doi.org/10.3390/polym13111752>



## Le recyclage et le réemploi: des enjeux majeurs à l'échelle européenne



<https://woodcircus.eu/> 2018-2021

Underpinning the vital role of the forest-based sector in the Circular Bioeconomy

**WoodCircus project's main goal is to promote wood-based value chains** as a key part of a circular bioeconomy in Europe. This goal is pursued by studying, assessing and highlighting efficiency of wood-based value chains in the wood construction sector. It englobes the mobilisation and first transformation of wood, building and construction activities, production side streams, reuse and recycling aspects. Contributing to the development of sustainable societies, it is expected to create more employment predominantly in rural areas in Europe by connecting them to the urbanisation process.

Facts & figures on the European construction sector



W2W: A Wood-to-Wood Cascade Upcycling Valorisation Approach

**lermab** 2024-2028

**Actuellement**

Bois collecté **6.886 Mt**  
 32% (2.2Mt) recyclé  
 70% = panneaux de particules



(AGEC 2023, REP)  
 Neutralité carbone France

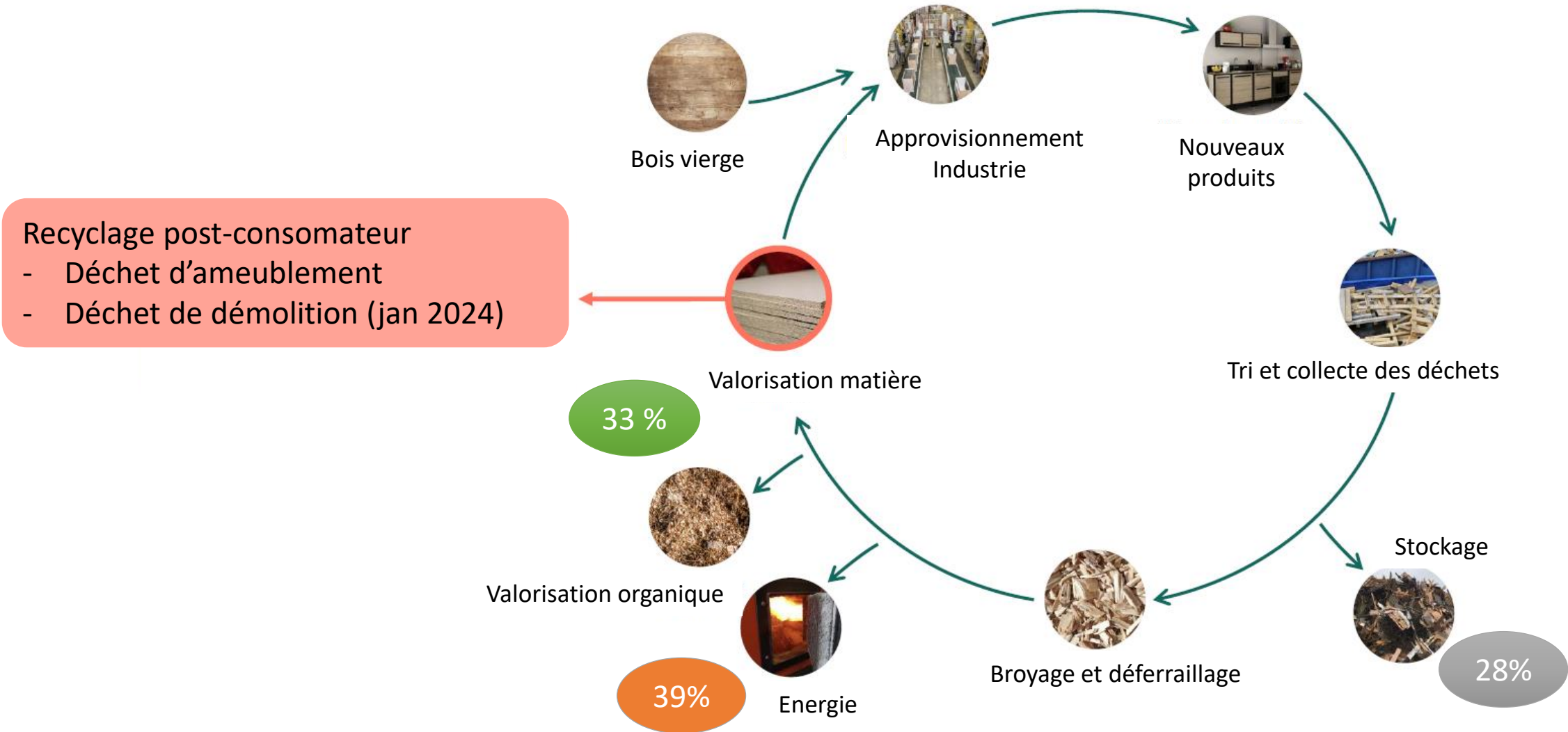
**2027 (début 2024)**

Bois collecté **8.1 Mt**



41% (3.32Mt) recyclé  
 40% (+10%) = bois de structure

# Recyclage du bois en France (bois A-BR1-BR2)

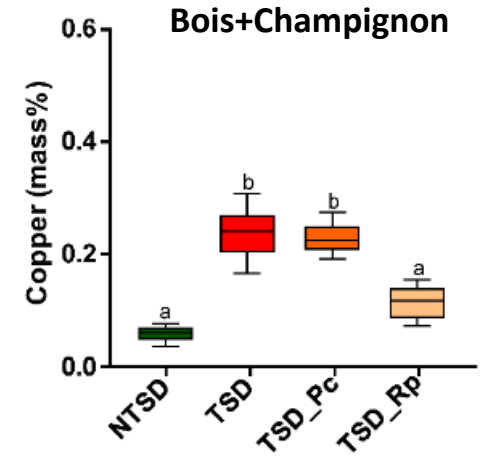
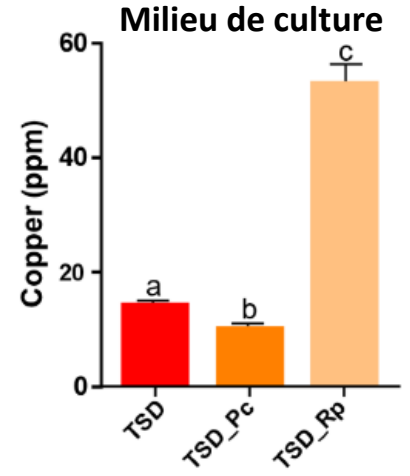
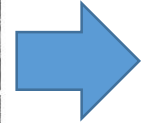
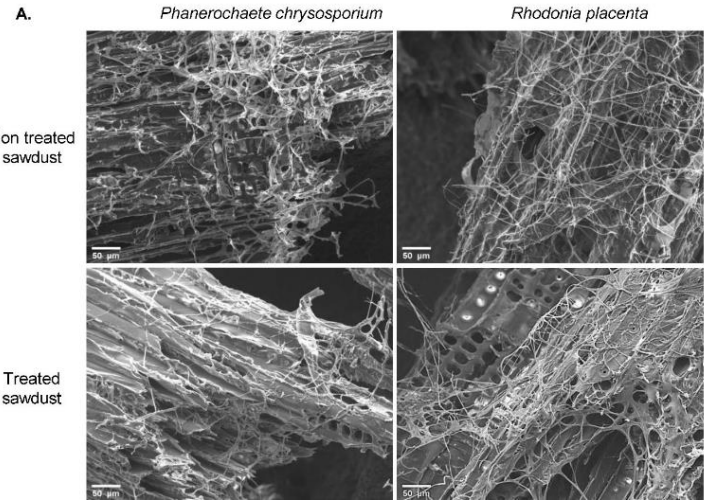
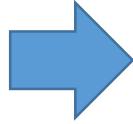


- Forte tension sur le bois de recyclage (Energie vs matière)
- Très peu de valorisation matière fibres (MDF) et bois C (imprégnés)

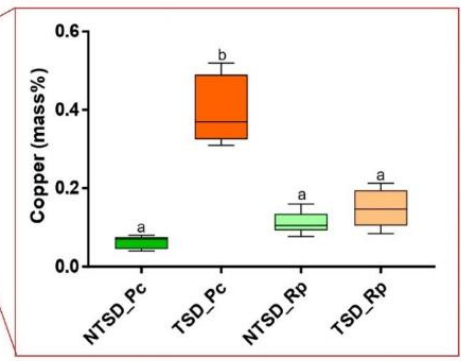
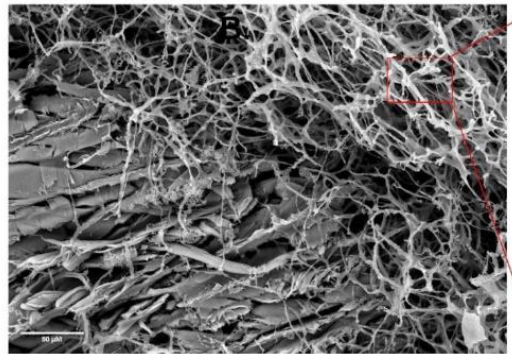


# Mycoremédiation de bois imprégné Cu/azole (bois C)

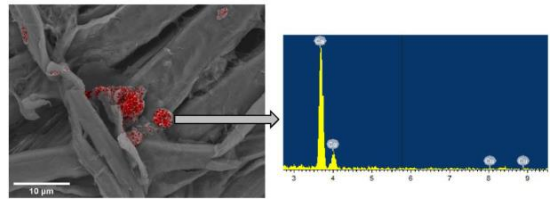
Bois imprégné Tanalith E 3474



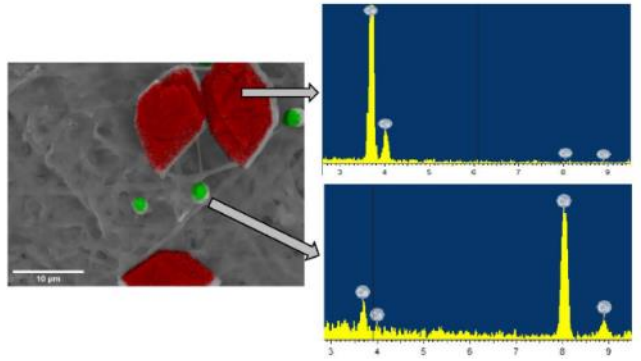
Cu dans le champignon



Pc



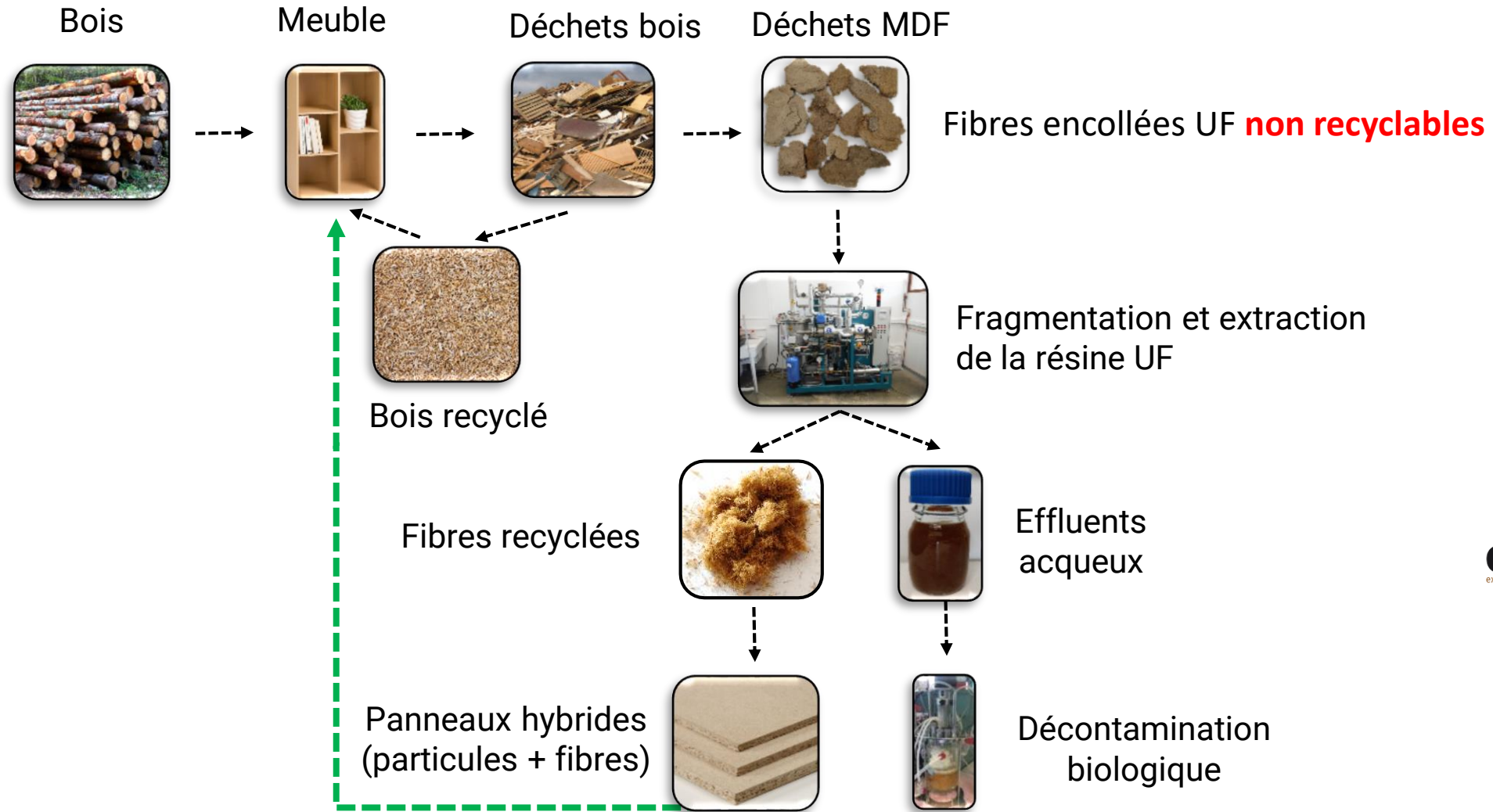
Rp



Tolérance à TE3474 =

Différents mécanismes biologiques

pourritures blanches et brunes



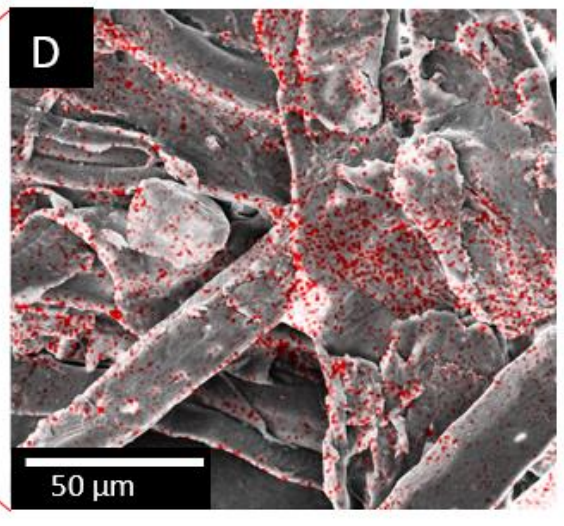
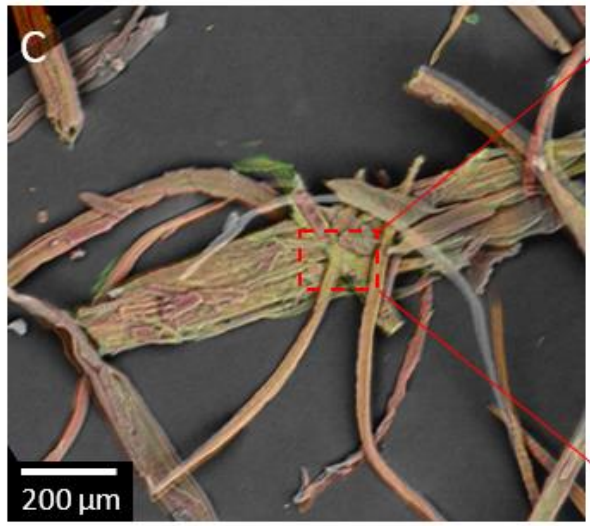
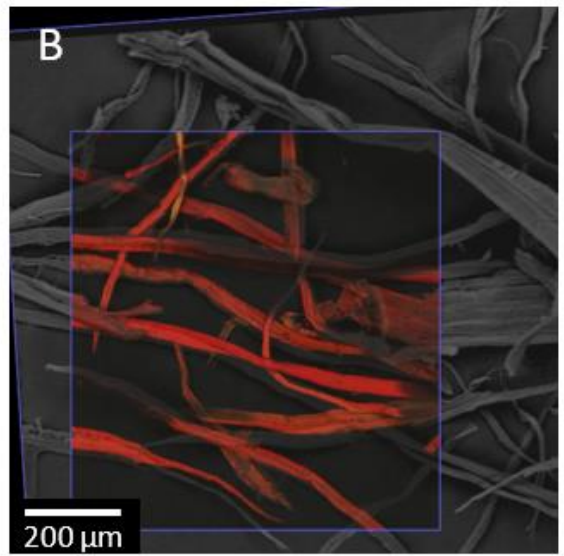
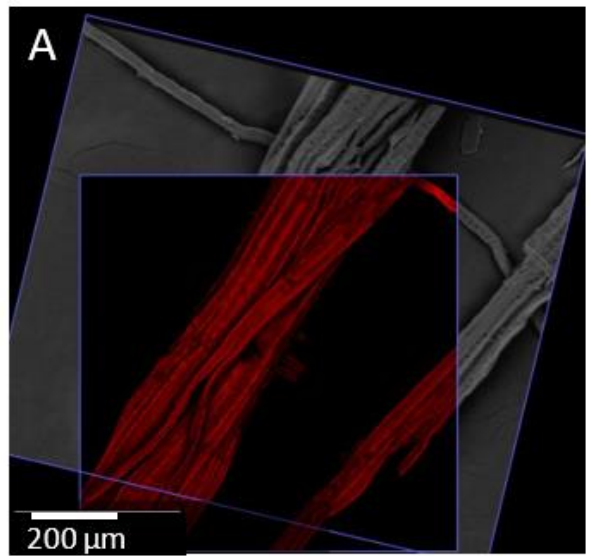
Thèse CIFRE Sarah Troilo (recyclage MDF) + Projet PROFEX



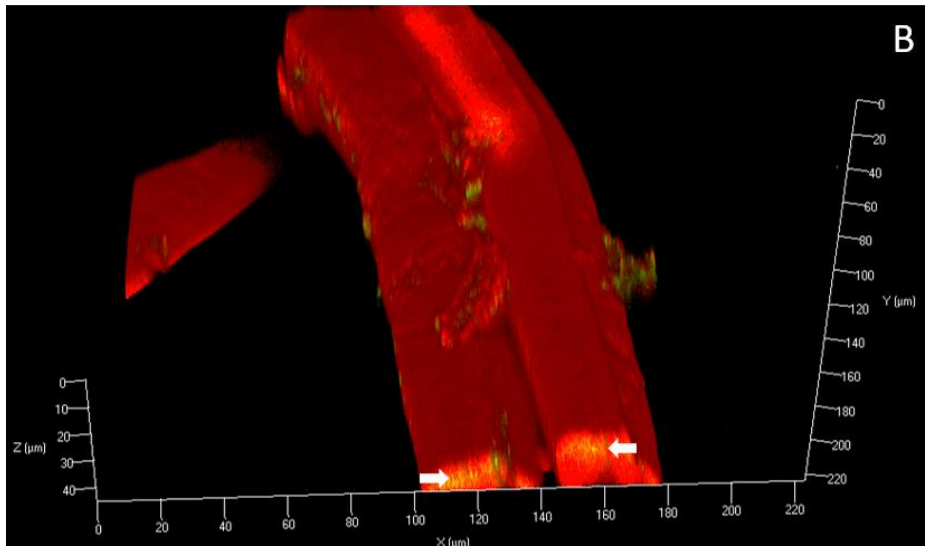
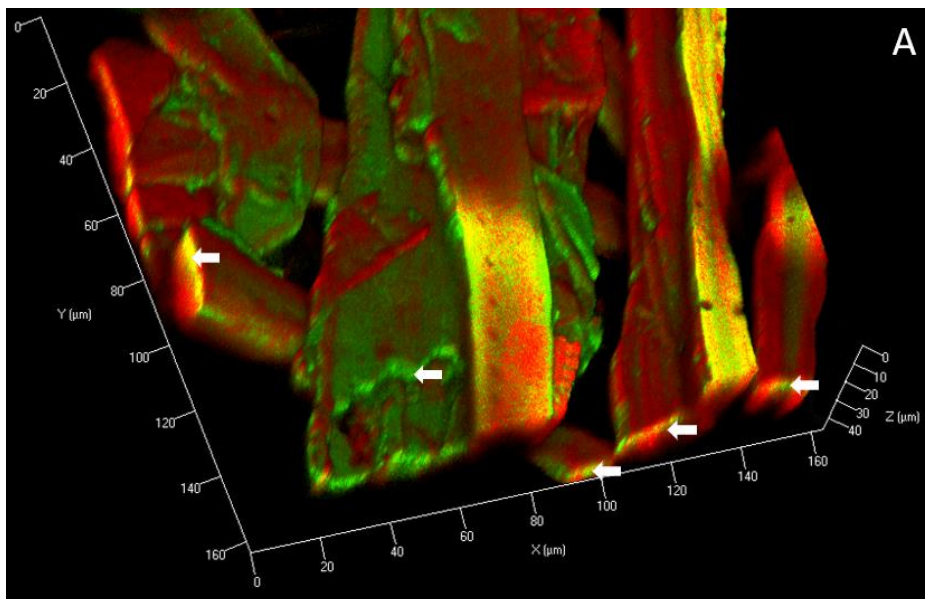
**Brevet :** Troilo S., Soufflet L., Brosse N., Besserer A., Girods P., 2022. Procédé et installation de traitements de déchets de panneaux de fibres de bois et panneaux fabriqués à partir de telles fibres recyclables FR22-02263.

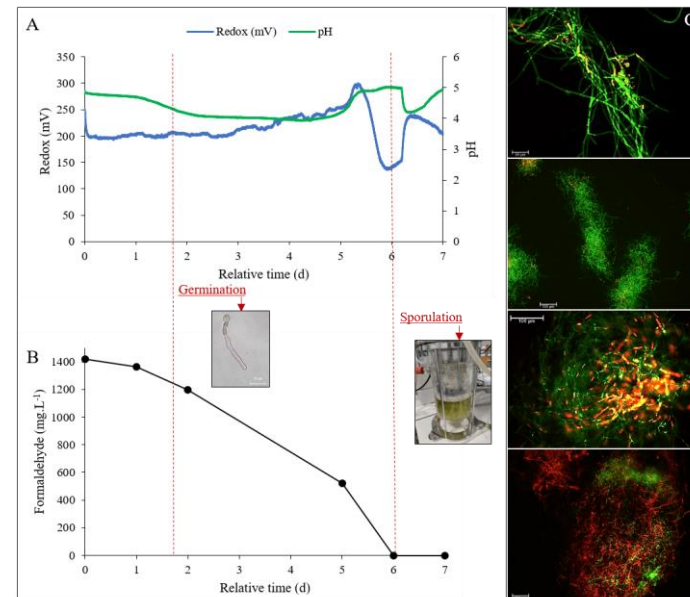
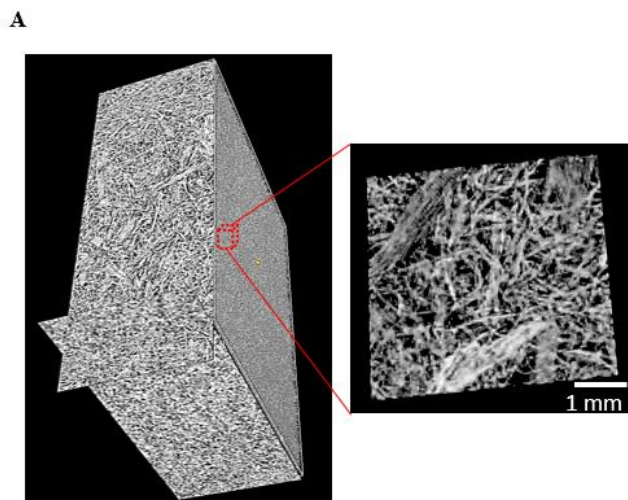
**Publications:**  
 - Besserer et al., 2021. <https://doi.org/10.3390/polym13111752>  
 - Troilo et al., 2023 <https://pubs.acs.org/doi/10.1021/acssuschemeng.2c05686>

## CLEM-EDS/WDS

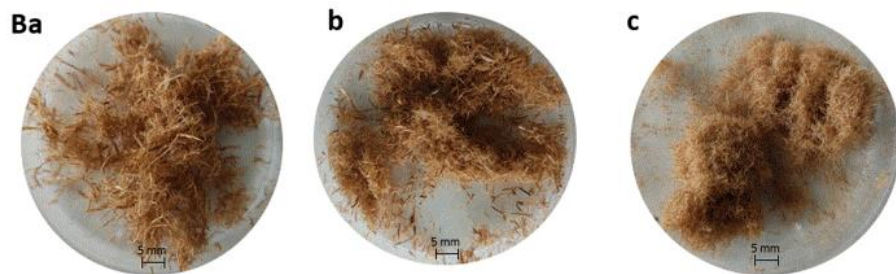


## 3D CLSM





Troilo et al., en cours de publication



Troilo et al., 2023  
<https://pubs.acs.org/doi/10.1021/acssuschemeng.2c05686>



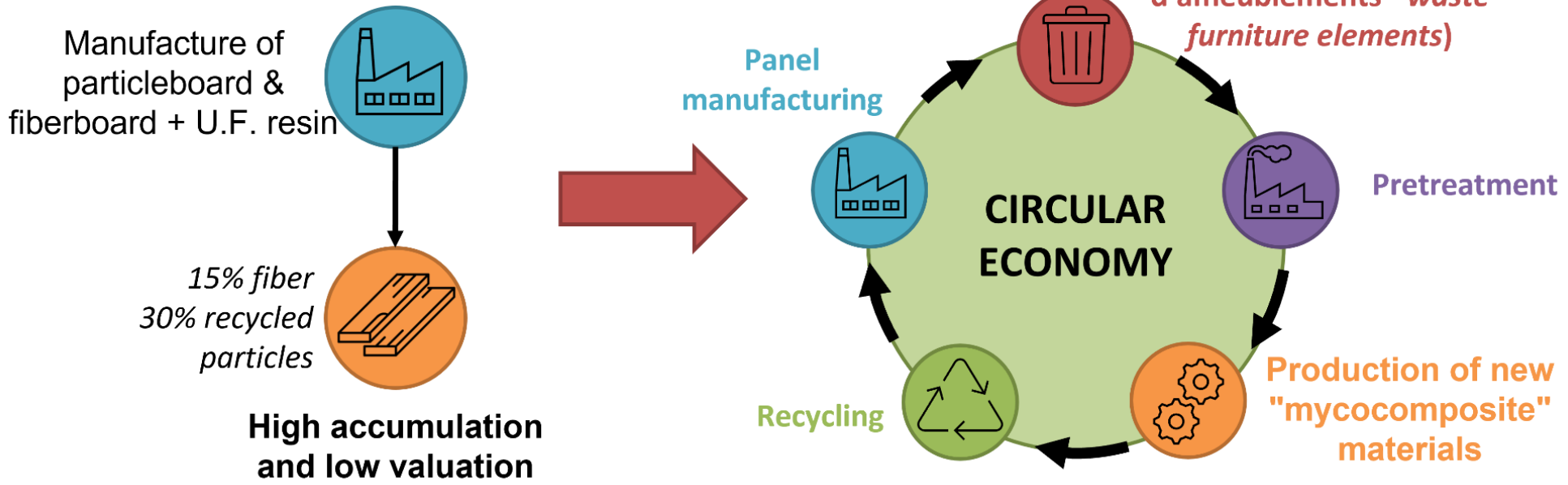
Troilo et al., en cours de publication

PLA

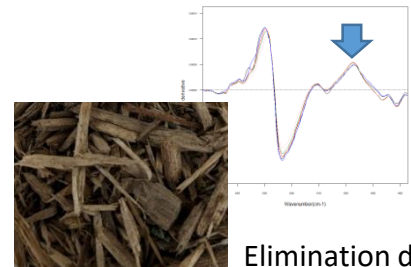
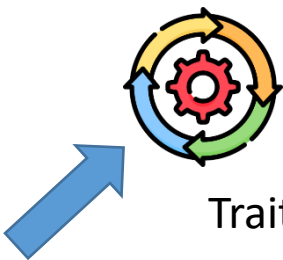
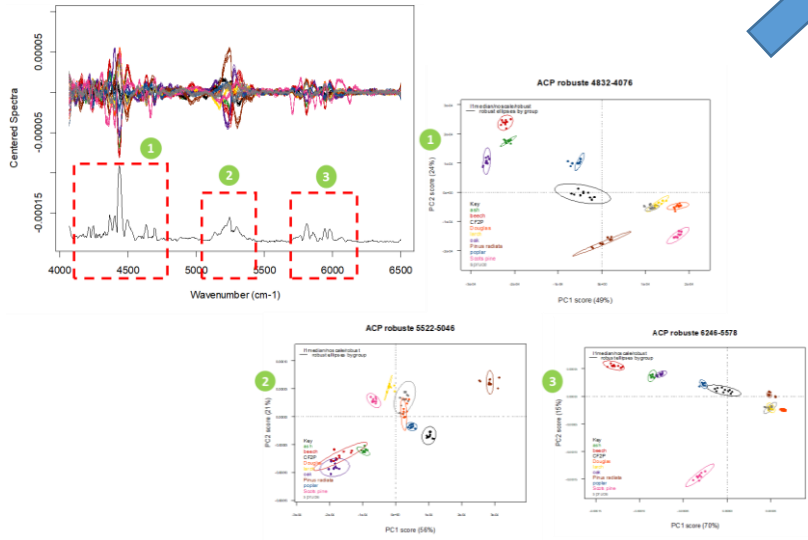


Thèse CIFRE  
J. Ramaux





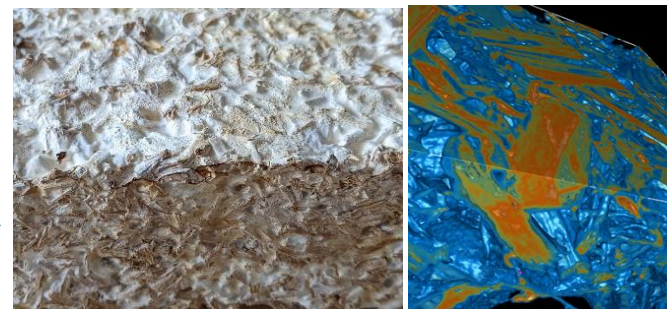
# Du bois recyclé aux mycocomposites



Elimination de la colle et fonctionnalisation



Mélange avec le champignon

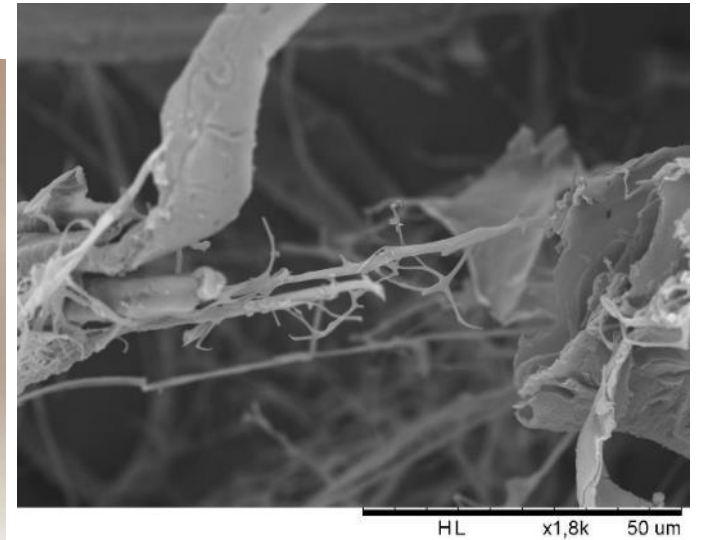
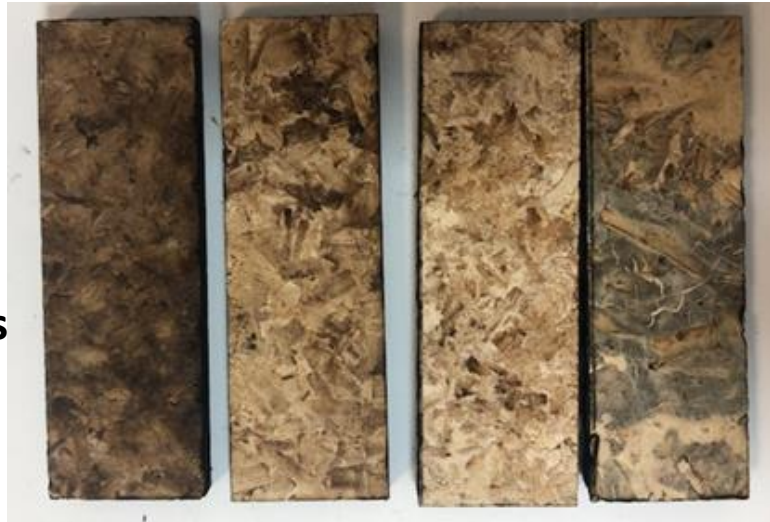
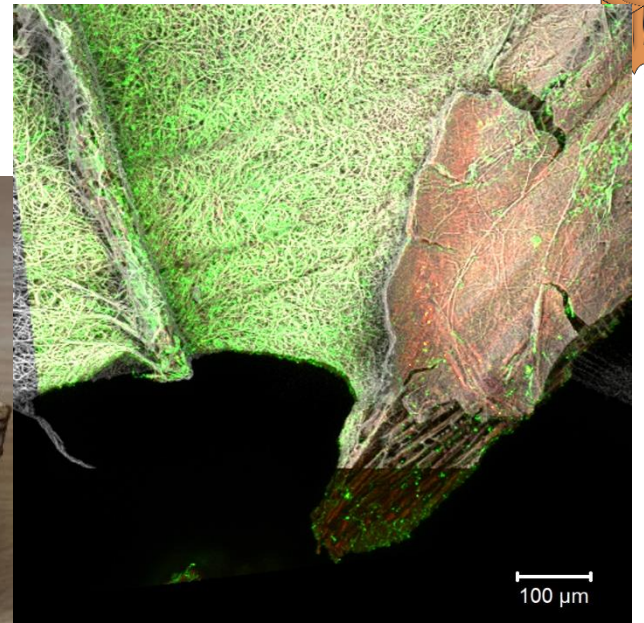
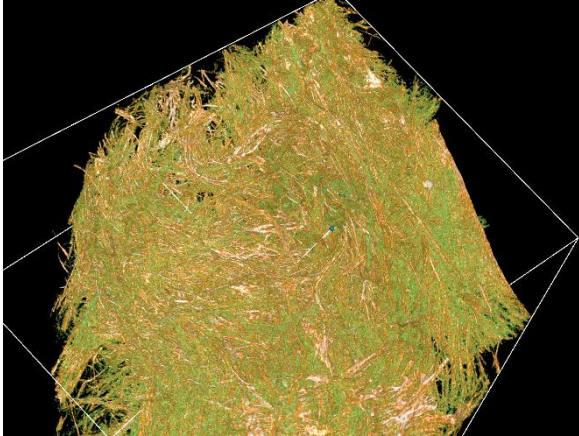


Mycocomposites



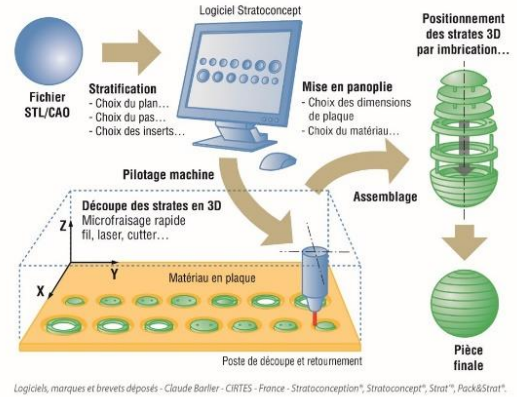
Analyse non destructive et détermination des essences et des contaminants

# Collage par le champignon



- 100% Biodégradable (compostable)
- Ignifugé
- Hautes performances thermiques et phoniques
- Hygroscopique (déphasage été/hiver)

# En cours...



Fréchard et al., 2023  
<https://doi.org/10.52202/069179-0482>



## Projet LUE Mycobat



Laura Figel



**Merci pour votre attention!**

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arnaud.besserer@univ-lorraine.fr