Bois & forêts des tropiques

2e trimestre 2024
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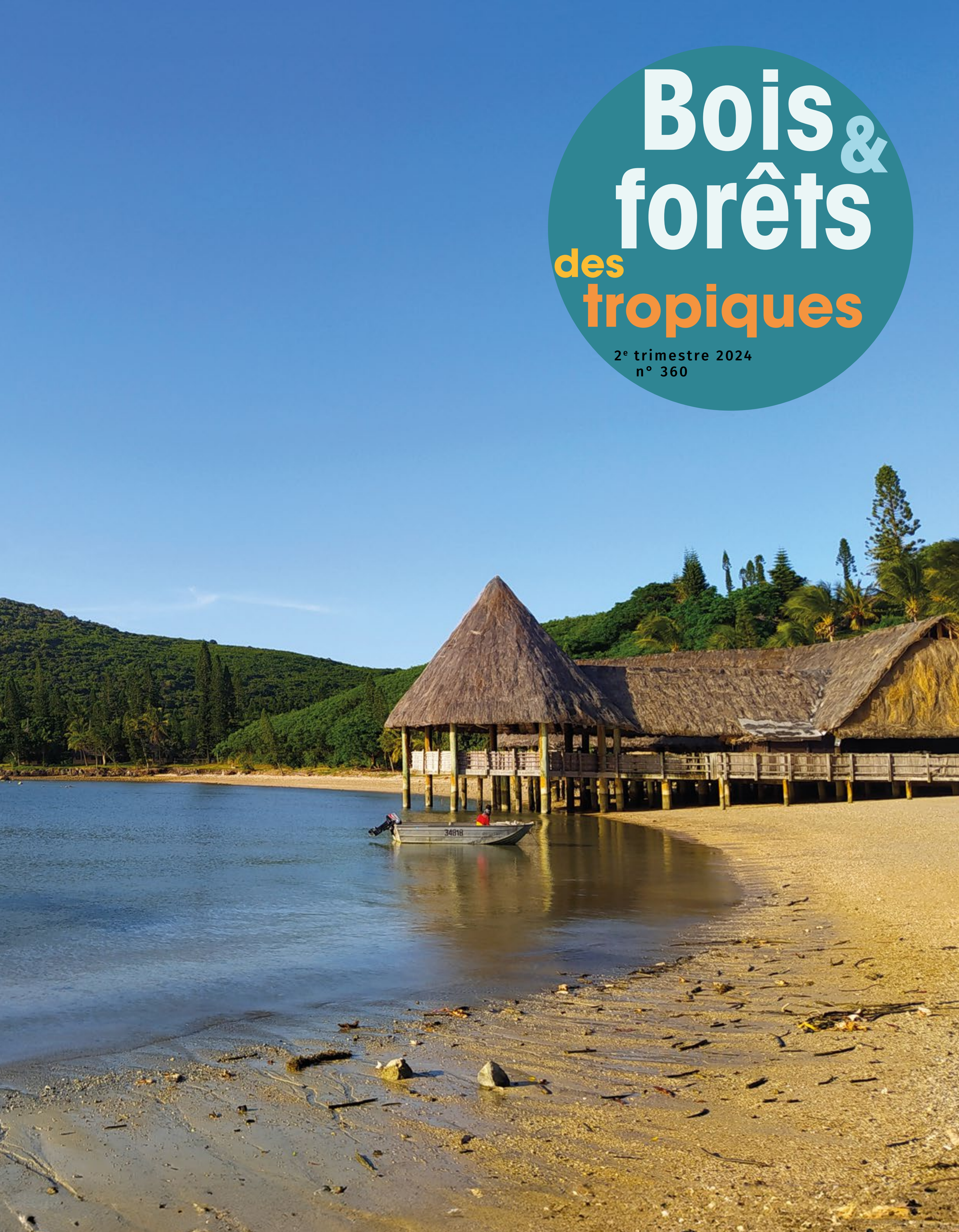

Bois & forêts des tropiques

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Ponton abrité, réalisé avec des poteaux en pin radiata (*Pinus insignis*) traités au CCA (*Chromated Copper Arsenate*), à Nouméa, Nouvelle Calédonie, France.
Covered dock, built with wooden poles in radiata pine (Pinus insignis) treated with CCA (Chromated Copper Arsenate), Nouméa, New Caledonia, France.
Photo K. Candelier.

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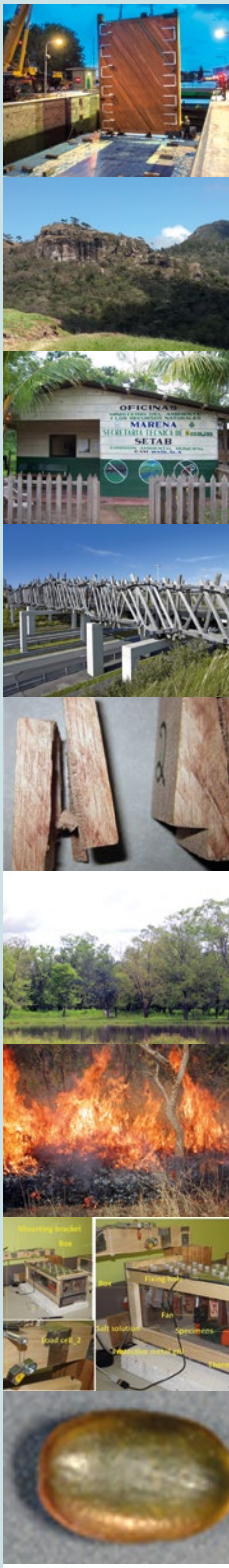

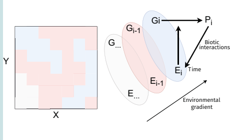

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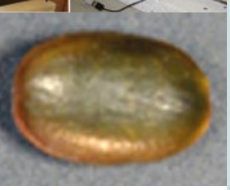
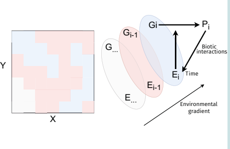

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ÉDITORIAL

Les bois tropicaux dans les ouvrages hydrauliques et les constructions marines

Les structures en bois utilisées pour des applications en milieux marins sont exposées à des environnements difficiles dans les zones littorales (Tsinker, 1995). Ces bois sont souvent exposés à de sévères conditions de dégradation causées par d'importantes charges mécaniques (poids, vagues, chocs de débris, etc.), par l'abrasion, mais surtout par de nombreux agents biologiques de dégradation du bois (Treu *et al.*, 2019). Que ce soit en contact avec l'eau salée, saumâtre (estuaires, lagunes) ou douce, et en fonction de leur niveau d'immersion, les bois sont soumis à de nombreuses attaques d'agents pathogènes tels que les bactéries, les champignons, les insectes et les térébrants marins (Oevering *et al.*, 2001 ; Cragg *et al.*, 2007 ; Can et Sivrikaya, 2020). Dans les eaux salées ou saumâtres, les mollusques et les crustacés térébrants sont les principaux agents de dégradation des bois utilisés pour les ouvrages immergés (Fouquet, 2009). Malgré sa biodégradabilité, le bois est un matériau d'intérêt pour la construction marine, notamment en raison de son caractère renouvelable, de sa résilience, de son rapport résistance/poids favorable, de sa capacité à absorber les chocs, mais aussi de sa flexibilité en matière de fabrication, de conception et de réparation (Williams *et al.*, 2005). En ce sens, l'utilisation du bois en milieu marin concurrence d'autres matériaux tels que l'acier ou le béton.

Par le passé, des traitements chimiques étaient appliqués au bois afin d'obtenir un produit utilisable en classe d'emploi 5 (EN 335, 2013 ; EN 350, 2016), pour le protéger vis-à-vis des attaques biotiques et ainsi prolonger sa durée de vie en environnement marin (photo 1). Cependant, l'impact négatif de ces types de traitements biocides à base de créosote ou de CCA (*Chromated Copper Arsenate*) sur la santé humaine et l'environnement, en raison des risques de lixiviation des produits actifs (Mercer et Frostick, 2012, Martin *et al.*, 2021), a conduit à leur interdiction en Europe et leur forte restriction aux États-Unis d'Amérique depuis 2003[1, 2]. Dès lors, de nombreux travaux de recherche se sont portés sur des solutions de traitements alternatives à base de cuivre alcalin quartenaire (ACQ-based preservative) (Hellkamp, 2012 ; Humar *et al.*, 2013), de 1,3-diméthylol 4,5-dihydroxy éthylène urée (DMDHEU), de résine de mélamine méthylée (MMF), d'anhydride acétique, de résine phénolique à base de formaldéhyde (PF) ou encore d'alcool furfurylique (Klüppel *et al.*, 2014 ; Westin *et al.*, 2016 ; Galore *et al.*, 2023). Cependant, les technologies de modification du bois actuellement disponibles concernent essentiellement des produits de niche qui ont un coût important, ce qui limite leur utilisation à des produits de plus grande valeur ajoutée (Treu *et al.*, 2019). À l'heure actuelle, aucun produit de préservation du bois n'est approuvé en Europe pour les applications marines. Les nouvelles méthodes de protection du bois doivent répondre à la fois aux exigences d'efficacité contre les organismes de dégradation du bois, mais aussi à l'absence d'effets secondaires nocifs pour les organismes non ciblés.

Certaines essences tropicales sont traditionnellement utilisées dans les travaux portuaires en régions tropicales et/ou tempérées, car considérées comme résistantes aux térébrants marins, couvrant naturellement la classe d'emploi 5 (bois immergés dans

Photo 1.
Ponton abrité, réalisé avec des poteaux en pin radiata (*Pinus insignis*) traités au CCA (*Chromated Copper Arsenate*), à Nouméa, Nouvelle Calédonie, France.
Photo K. Candelier.

033: Pin sylvestre (*Pinus sylvestris*) après 1 an
025: Acaria (*Minquartia guianensis*) après 22 ans
072: Azobé/Ekki (*Lophira alata*) après 8 ans
322: Angelique (*Dicorynia guianensis*) après 6 ans

Photo 2.
Bois tropicaux testés en milieu marin, depuis 1999 et conformément à la norme EN 275 (1992), sur le site de la station de recherche marine de Kristineberg en Suède (Westin et Brelid, 2022).
Photo M. Westin et P. L. Brelid.

Photo 3.
Utilisation de bois tropicaux en ouvrage hydraulique : pose d'une porte d'écluse en Azobé.
Photo Entreprise Wijma (Deventer, Pays-Bas), extrait de Gérard et Groutel (2020).

[1] Journal officiel de l'Union européenne, Directive 2003/2/EC du 6 janvier 2003, Clause (3).
[2] Agence américaine pour la protection de l'environnement, https://www.epa.gov/ingredients-used-pesticide-products/chromated-arsenicals-cca, consulté le 2 octobre 2024.

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l'eau salée, eau de mer ou eau saumâtre, de manière régulière ou permanente) : angelim vermelho, azobé, greenheart, okan, wallaba[3]... Cependant, les marchés de certaines de ces essences les plus couramment utilisées (azobé, okan, greenheart) apparaissent de plus en plus en tension avec une irrégularité des approvisionnements qui incite les entreprises spécialisées dans les travaux portuaires à se tourner vers de nouvelles essences (photo 2) avec des propriétés au moins équivalentes. Les essences de bois tropicales moins connues sont difficiles à commercialiser en raison du manque de données issues d'essais fiables sur leurs performances, en particulier sur leur durabilité naturelle. Pour ces nouvelles essences, la résistance aux térébrants marins doit être aujourd'hui validée en laboratoire ou par des expérimentations en conditions réelles d'utilisation, dans le but de contribuer positivement à l'utilisation des bois tropicaux dans les structures marines (photo 3).

Par ailleurs, on observe une évolution des attaques des térébrants marins sur les bois, celles-ci « migrant » vers le nord en relation avec une tendance au réchauffement des eaux marines et un élargissement de l'aire naturelle de répartition de ces térébrants (lien supposé avec le réchauffement climatique, Zarzyczny *et al.*, 2023) (figure 1). Cette évolution impacte le comportement des bois classiquement utilisés en milieu marin, certaines essences réputées très durables s'avérant moins résistantes que d'autres jusqu'à présent délaissées pour ce type d'usage (Palanti *et al.*, 2015 ; Williams *et al.*, 2018).

Les connaissances actuelles sur la résistance des bois aux attaques des agents biologiques de détérioration en milieu marin sont donc partiellement remises en question. Cette résistance naturelle est supposée être liée aux caractéristiques suivantes (Gérard et Groutel, 2020) : (1) grain fin à très fin couplé à une densité élevée ; (2) taux de silice élevé ; (3) présence dans le bois de composés chimiques répulsifs (= métabolites secondaires).

En effet, les bois utilisables pour des ouvrages hydrauliques en milieu marin présentent pour la plupart une densité moyenne supérieure à 0,75, cette densité moyenne étant le plus souvent supérieure à 0,85 (figure 2).

Il est encore aujourd'hui nécessaire, (i) de mieux comprendre comment et pourquoi les xylophages marins attaquent le bois, et (ii) de se concentrer davantage sur les différentes espèces d'organismes xylophages et sur leur mode d'action en fonction de la nature des différents bois testés. La mise en place de sites d'essais, permanents et temporaires, permettrait de surveiller l'abondance et la répartition des espèces et l'évolution des risques liés pour les matériaux bois.

Jean Gérard[1*], Marie-France Thévenon[1], Emmanuel Groutel[2], Kévin Candelier[1**]**
*Rédacteur scientifique, **Rédactrice et rédacteur en chef de la revue *Bois et Forêts des Tropiques*.
[1] Cirad, UPR BioWooEB, [2] Wale, Wood And Logistics Expert.
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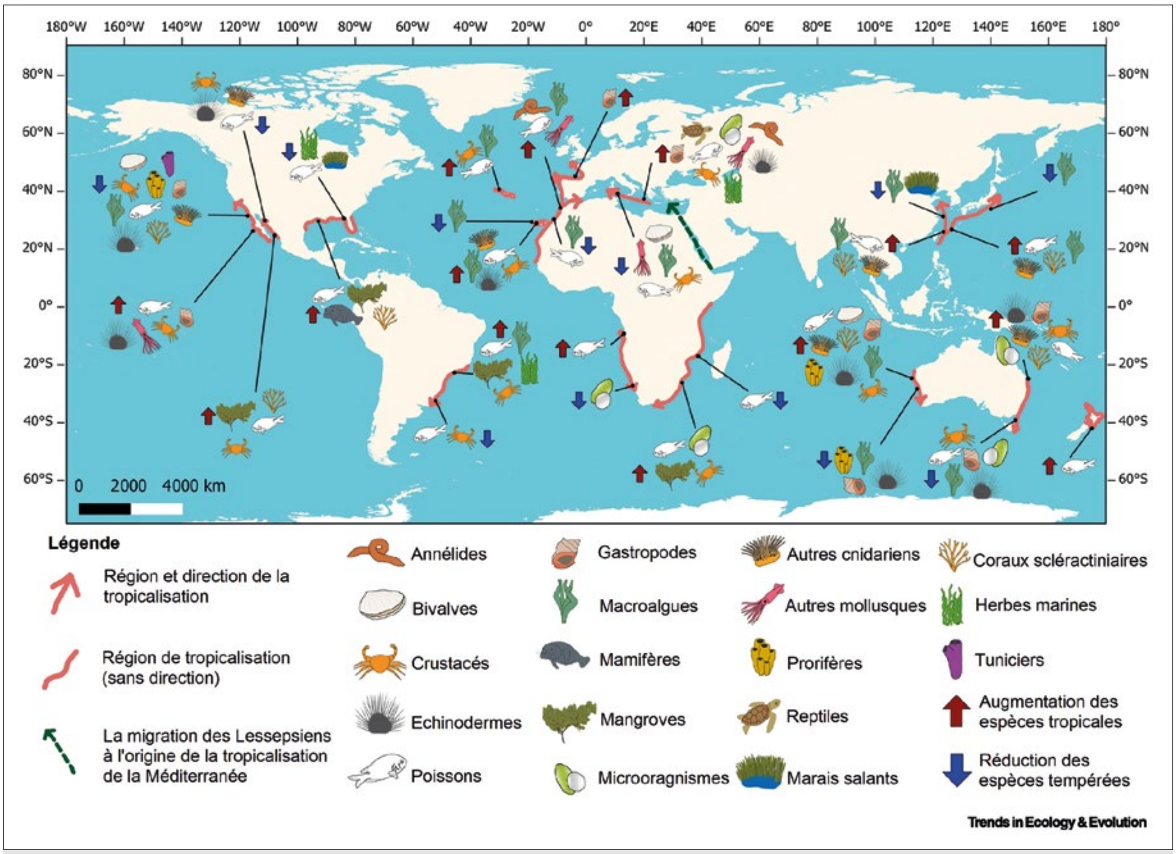

Figure 1.
Zones géographiques où la « tropicalisation » a été identifiée. La flèche rouge vers le haut indique une augmentation des espèces marines tropicales et la flèche bleue vers le bas une réduction des espèces tempérées (Zarzyczny *et al.*, 2023).

[3] Respectivement *Dinizia excelsa*, *Lophira alata*, *Chlorocardium rodiei*, *Cylicodiscus gabunensis*, *Eperua* p.p.

Références bibliographiques

Can A., Sivrikaya H., 2020. Evaluation of Marine Wood Boring Organism's Attack on Wood Materials in the Black Sea Coastal Region. Bioresources, 15 (2): 4271-4281. https://doi.org/10.15376/biores.15.2.4271-4281

Cragg S. M., Danjon C., Mansfield-Williams H., 2007. Contribution of hardness to the natural resistance of a range of wood species to attack by the marine borer *Limnoria*. Holzforschung, 61 (2): 201-206. https://doi.org/10.1515/HF.2007.035

EN 275, 1992. Standard Current Wood preservatives. Determination of the protective effectiveness against marine borers. European Standardization System, Bruxelles, Belgium, 25 p.

EN 335, 2013. Durability of wood and wood-based products – Use classes: definitions, application to solid wood and wood-based products. European Standardization System, Belgium, 17 p.

EN 350, 2016. Standard Current Durability of wood and wood-based products - Testing and classification of the durability to biological agents of wood and wood-based materials. European Standardization System, Belgium, 69 p.

Fouquet D., 2009. Durabilité naturelle et préservation des bois tropicaux. Éditions Quae, Collection Guide pratique, 128 p.

Galore E. L. D., Norton J., Zahora A., 2023. Long-term Performance of Treated Timbers in a Sub-tropical Marine Exposure. IRG54 annual conference, 05-28/06-01, Cairns, Australia, IRG/WP 23-11015. https://irg-wp.com/irgdocs/details.php?2b215f31-0afa-2040-0c9d-5b7a226d386d

Gérard J., Groutel E., 2020. Timber for hydraulic structures [In French]. France, ATIBT, 18 p. https://www.atibt.org/files/upload/technical-publications/publications-bois-tropical/14-LES-BOIS-POUR-OUVRAGES-HYDRAULIQUES.pdf

Hellkamp S., 2012. Wood in marine structures – Fouling organisms in sea water, T*eredo* ssp. and *Limnoria* ssp. Live cycle, attack pattern, and consequences for wood structures [In German]. Deutsche Holzschutztagung [German Wood Protection Symposium], Cuvillier, Germany, 46-51.

Humar M., Petric M., Adamek J., Lesar B., 2013. Performance of untreated wood and wood impregnated with copper-ethanolamine based preservative solutions in Northern Adriatic Sea. IRG44 annual conference, 16-20/06, Sweden, IRG/WP 13-30623. https://irg-wp.com/irgdocs/details.php?3548ce15-1f03-34bd-b291-6f4c3eb5cff2

Klüppel A., Mai C., Militz H., Cragg S., 2014. Performance of some wood modification treatments against marine borers. IRG45 annual conference, 11-15/05, St George, Utah, USA, IRG/WP 14-40668. https://www.irg-wp.com/irgdocs/details.php?4275c5e2-aef4-4a06-324d-afca136ecdec

Martin L. S., Jelavić S., Cragg S. M., Thygesen L. G., 2021. Furfurylation protects timber from degradation by marine wood boring crustaceans. Green Chemistry, 23: 8003–8015. https://doi.org/10.1039/D1GC01524A

Mercer T. G., Frostick L. E., 2012. Leaching characteristics of CCA-treated wood waste: A UK study. Science of The Total Environment, 427-428: 165-174. https://doi.org/10.1016/j.scitotenv.2012.04.008

Oevering P., Matthews B. J., Cragg S. M., Pitman A. J., 2001. Invertebrate biodeterioration of marine timbers above mean sea level along the coastlines of England and Wales. International Biodeterioration & Biodegradation, 47 (3): 175-181. https://doi.org/10.1016/S0964-8305(01)00046-4

Palanti S., Feci E., Anichini M., 2015. Comparison between four tropical wood species for their resistance to marine borers (*Teredo* spp and *Limnoria* spp) in the Strait of Messina. International Biodeterioration & Biodegradation, 104: 472-476. https://doi.org/10.1016/j.ibiod.2015.07.013

Treu A., Zimmer K., Brischke C., Larnoy E., Gobakken L.R., Aloui F., Cragg S.M., et al., 2019. Durability and protection of timber structures in marine environments in Europe: An overview. Bioresources, 14 (4): 10161-10184. https://doi.org/10.15376/biores.14.4.Treu

Tsinker G. P., 1995. The dock-in-service: Evaluation of load carrying capacity, repair, rehabilitation. Marine Structures Engineering: Specialized Applications, Springer, USA, 1-104. https://doi.org/10.1007/978-1-4615-2081-8

Westin M., Brelid P. L., Nilsson T., Rapp A.O., Dickerson J.P., Lande S., et al., 2016. Marine Borer Resistance of Acetylated and Furfurylated Wood - Results from up to 16 years of Field Exposure. IRG47 annual conference, 15-19/05, Portugal, IRG/WP 16-40756. https://www.irg-wp.com/irgdocs/details.php?3d10b0b4-411a-32f2-b392-0d9aa4644a09

Westin M., Brelid P. L., 2022. Field tests of different tropical wood species in sea water. IRG54 annual conference, 29-05/02-06, Bled, Slovenia, IRG/WP 22-30773. https://irg-wp.com/irgdocs/details.php?61d6cc04-f1b3-d893-b370-26ea38c48614

Williams J. R., Sawyer G. S., Cragg S. M., Simm J., 2005. A questionnaire survey to establish the perceptions of UK specifiers concerning the key material attributes of timer for use in marine and fresh water engineering. Journal of the Institute of Wood Science, 17 (1): 41-50. https://doi.org/10.1179/wsc.2005.17.1.41

Williams J. R., Sawyer G. S., Cragg S. M., Icely J. D., Simm J., Meaden M., et al., 2018. Evaluating less-used timber species for marine construction. Proceedings of the Institution of Civil Engineers - Construction Materials, 171 (4): 134-148. https://doi.org/10.1680/jcoma.15.00065

Zarzyczny K. M., Rius M., Williams S. T., Fenberg P. B., 2024. The ecological and evolutionary consequences of topicalization. Trends in Ecology & Evolution, 39 (3): 267-279. https://doi.org/10.1016/j.tree.2023.10.006

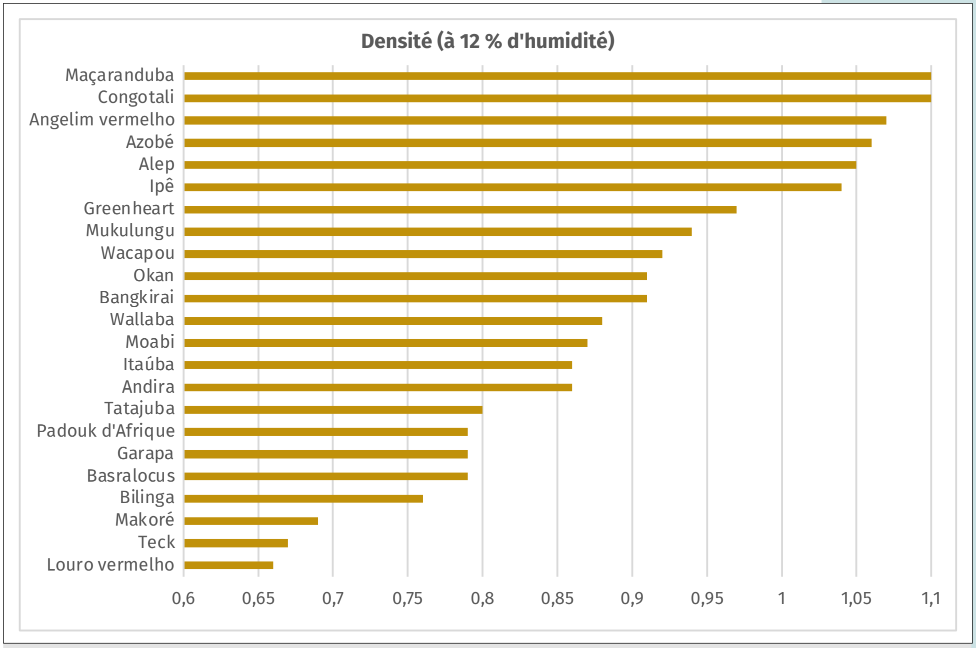

Figure 2.
Répartition des densités des principaux bois commerciaux couvrant naturellement la classe d'emploi 5 (bois immergés dans l'eau salée de manière régulière ou permanente), source : Tropix (Gérard et Groutel, 2020).

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Tropical woods in hydraulic works and marine constructions

Photo 1.
Covered dock, made with wooden poles in radiata pine (*Pinus insignis*) treated with CCA (Chromated Copper Arsenate), Nouméa, New Caledonia, France.
Photo K. Candelier.

Photo 2.
Tropical woods tested in a marine environment, since 1999 and in agreement with the guidelines of EN 275 (1992), at the Kristineberg marine research station in Sweden (Westin and Brelid 2022).
Photo M. Westin & P. L. Brelid.

Photo 3.
Use of tropical woods in hydraulic works: installation of an Azobe lock gate.
Photo Wijma company (Deventer, Netherlands), from Gérard & Groutel (2020).

Wood structures used for marine applications are exposed to harsh environments in coastal areas (Tsinker 1995). These woods are often subjected to severe degradation conditions caused by significant mechanical loads (weight, waves, shock of fragments, etc.), abrasion, and especially by numerous biological agents that degrade wood (Treu et al. 2019). Whether in contact with saltwater, brackish water (estuaries, lagoons) or freshwater, and depending on their level of immersion, woods are subjected to many attacks from pathogens such as bacteria, fungi, insects, and marine borers (Oevering et al. 2001; Cragg et al. 2007; Can and Sivrikaya 2020). In salt or brackish waters, mollusks and marine borers are the main agents of degradation for wood used in submerged structures (Fouquet 2009). Despite its biodegradability, wood is a material of interest for marine construction due to its renewable nature, resilience, favourable strength-to-weight ratio, shock-absorbing ability, and flexibility in manufacturing, design and repair (Williams et al. 2005). In this sense, the use of wood in marine environments competes with other materials such as steel or concrete.

In the past, chemical treatments were applied to wood to obtain a product covering use class 5 (EN 335 2013; EN 350 2016), to protect it against biotic attacks and extend its lifespan in marine environments (photo 1). However, the negative impact of these biocidal treatments, based on creosote or chromated copper arsenate (CCA), on human health and the environment (Mercer and Frostick 2012, Martin et al. 2021) has led to their ban in Europe and their extended restriction in the United-States of America since 2003[1, 2]. Many research efforts have focused on alternative treatment solutions based on alkaline copper quaternary (ACQ) (Hellkamp 2012; Humar et al. 2013), 1,3-dimethylol-4,5-dihydroxyethylene urea (DMDHEU), methylated melamine resin (MMF), acetic anhydride, formaldehyde-based phenolic resin (PF), or furfuryl alcohol (Klüppel et al. 2014; Westin et al. 2016, Galore et al. 2023). However, currently available wood modification technologies mainly concern niche products that are costly, limiting their use to higher value-added products (Treu et al., 2019). As of now, no wood preservation product is approved in Europe for marine applications. New methods must meet efficiency requirements against degrading organisms while avoiding harmful side effects.

Some tropical species are traditionally used in port works in tropical and/or temperate areas, because they are considered resistant to marine borers, naturally covering use class 5 (wood regularly or permanently immersed in salt water, sea water or brackish water): Angelim Vermelho, Azobe, Greenheart, Okan, Wallaba[3].... However, markets for some of these species appear strained with irregular supply that encourages turning to new species (photo 2) with at least

[1] Official Journal of the European Communities Commission, Directive 2003/2/EC of 6th January 2003, Clause (3).
[2] United States Environment Protection Agency, https://www.epa.gov/ingredients-used-pesticide-products/chromated-arsenicals-cca, consulted the 02/10/2024.
[3] Respectively *Dinizia excelsa*, *Lophira alata*, *Chlorocardium rodiei*, *Cylicodiscus gabunensis*, and *Eperua* p.p.

equivalent properties. The natural resistance of new species to marine borers must be validated through laboratory experiments or real-use conditions to positively contribute to the use of tropical woods in marine structures.

Lesser-known tropical wood species are difficult to promote due to the lack of reliable test data on their performance, particularly their natural durability. The resistance of these new species to marine borer attacks now needs to be checked in the laboratory or through experiments under real conditions of use, to contribute positively to the use of tropical woods in marine structures (photo 3).

There is also an observed evolution in the attacks on wood materials by marine borers migrating northward in relation to warming sea waters and an expansion of the natural area of these microorganisms (supposedly linked to global warming, Zarzyczny et al. 2023) (figure 1). This evolution impacts the behaviour of traditionally used woods in marine environments, some species considered highly durable are proving to be less resistant than others so far disregarded for this type of use (Palanti et al. 2015; Williams et al. 2018).

Current knowledge about wood resistance against biological attacks in marine context is therefore partially called into question. This natural resistance is thought to be linked to some characteristics (Gérard and Groutel 2020), such as (1) fine grain coupled with high specific gravity; (2) high silica content; (3) presence of repellent chemical compounds (= secondary metabolites) in wood.

In fact, most woods used for hydraulic structures in the marine environment have an average specific gravity of over 0.75, and this average specific gravity is most often over 0.85 (figure 2).

There is still a need (i) to better understand how and why marine woodborers attack wood, and (ii) to focus more closely on the different species of woodborer and their degradation ways in relation to the nature of the woods tested. Setting up permanent and temporary test sites would make it possible to monitor the pressure and distribution of marine species and the evolution of related risks for wood materials.

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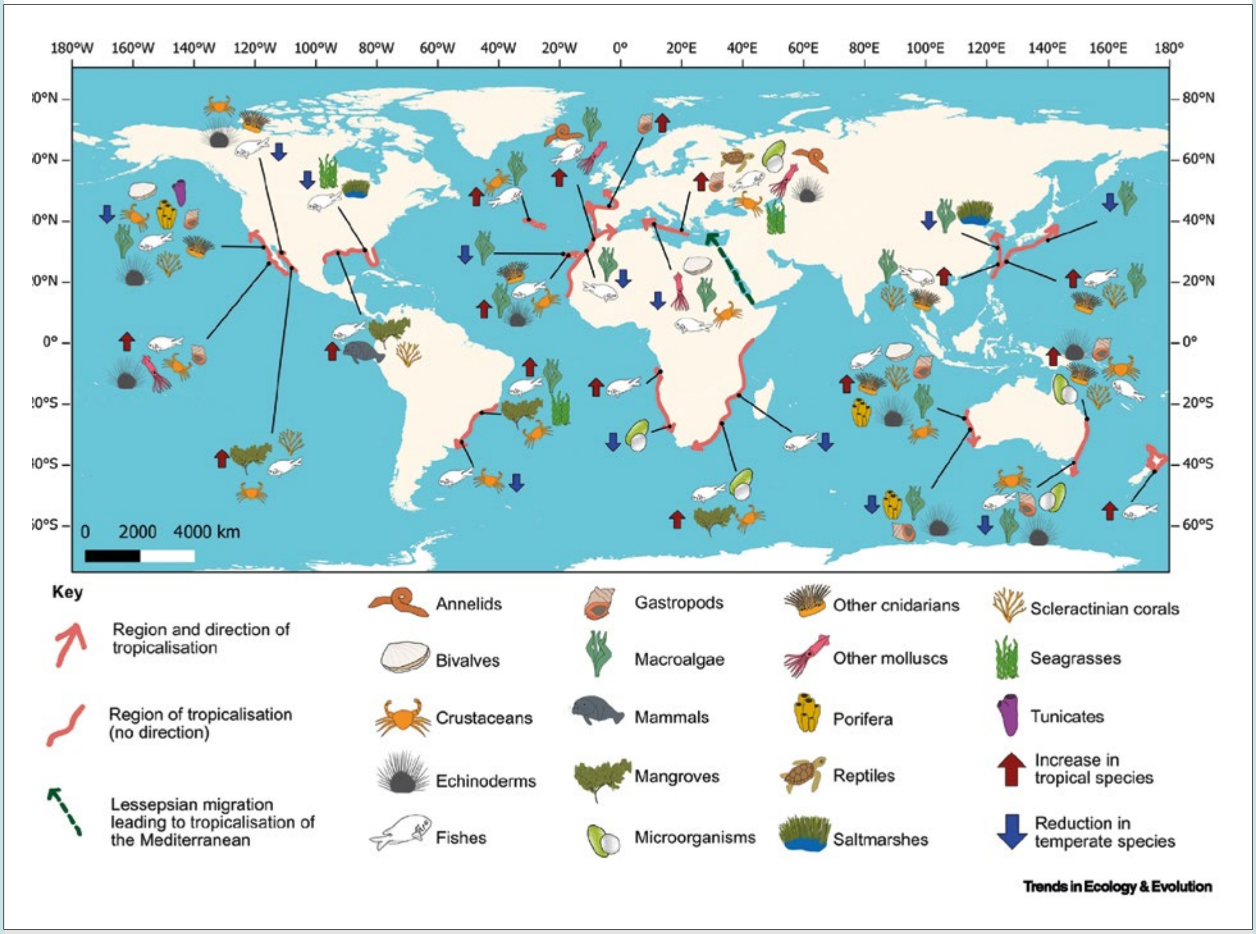

Figure 1.
Geographical areas where "tropicalisation" has been identified. The red upward arrow indicates an increase in tropical marine species and the blue downward arrow means a reduction in temperate species (Zarzyczny et al. 2023).

References

Can A., Sivrikaya H., 2020. Evaluation of Marine Wood Boring Organism's Attack on Wood Materials in the Black Sea Coastal Region. Bioresources, 15 (2): 4271-4281. https://doi.org/10.15376/biores.15.2.4271-4281

Cragg S. M., Danjon C., Mansfield-Williams H., 2007. Contribution of hardness to the natural resistance of a range of wood species to attack by the marine borer *Limnoria*. Holzforschung, 61 (2): 201-206. https://doi.org/10.1515/HF.2007.035

EN 275, 1992. Standard Current Wood preservatives. Determination of the protective effectiveness against marine borers. European Standardization System, Bruxelles, Belgium, 25 p.

EN 335, 2013. Durability of wood and wood-based products – Use classes: definitions, application to solid wood and wood-based products. European Standardization System, Belgium, 17 p.

EN 350, 2016. Standard Current Durability of wood and wood-based products - Testing and classification of the durability to biological agents of wood and wood-based materials. European Standardization System, Belgium, 69 p.

Fouquet D., 2009. Durabilité naturelle et préservation des bois tropicaux. Éditions Quae, Collection Guide pratique, 128 p.

Galore E. L. D., Norton J., Zahora A., 2023. Long-term Performance of Treated Timbers in a Sub-tropical Marine Exposure. IRG54 annual conference, 05-28/06-01, Cairns, Australia, IRG/WP 23-11015. https://irg-wp.com/irgdocs/details.php?2b215f31-0afa-2040-0c9d-5b7a226d386d

Gérard J., Groutel E., 2020. Timber for hydraulic structures [In French]. France, ATIBT, 18 p. https://www.atibt.org/files/upload/technical-publications/publications-bois-tropical/14-LES-BOIS-POUR-OUVRAGES-HYDRAULIQUES.pdf

Hellkamp S., 2012. Wood in marine structures – Fouling organisms in sea water, T*eredo* ssp. and *Limnoria* ssp. Live cycle, attack pattern, and consequences for wood structures [In German]. Deutsche Holzschutztagung [German Wood Protection Symposium], Cuvillier, Germany, 46-51.

Humar M., Petric M., Adamek J., Lesar B., 2013. Performance of untreated wood and wood impregnated with copper-ethanolamine based preservative solutions in Northern Adriatic Sea. IRG44 annual conference, 16-20/06, Sweden, IRG/WP 13-30623. https://irg-wp.com/irgdocs/details.php?3548ce15-1f03-34bd-b291-6f4c3eb5cff2

Klüppel A., Mai C., Militz H., Cragg S., 2014. Performance of some wood modification treatments against marine borers. IRG45 annual conference, 11-15/05, St George, Utah, USA, IRG/WP 14-40668. https://www.irg-wp.com/irgdocs/details.php?4275c5e2-aef4-4a06-324d-afca136ecdec

Martin L. S., Jelavić S., Cragg S. M., Thygesen L. G., 2021. Furfurylation protects timber from degradation by marine wood boring crustaceans. Green Chemistry, 23: 8003–8015. https://doi.org/10.1039/D1GC01524A

Mercer T. G., Frostick L. E., 2012. Leaching characteristics of CCA-treated wood waste: A UK study. Science of The Total Environment, 427-428: 165-174. https://doi.org/10.1016/j.scitotenv.2012.04.008

Oevering P., Matthews B. J., Cragg S. M., Pitman A. J., 2001. Invertebrate biodeterioration of marine timbers above mean sea level along the coastlines of England and Wales. International Biodeterioration & Biodegradation, 47 (3): 175-181. https://doi.org/10.1016/S0964-8305(01)00046-4

Palanti S., Feci E., Anichini M., 2015. Comparison between four tropical wood species for their resistance to marine borers (*Teredo* spp and *Limnoria* spp) in the Strait of Messina. International Biodeterioration & Biodegradation, 104: 472-476. https://doi.org/10.1016/j.ibiod.2015.07.013

Treu A., Zimmer K., Brischke C., Larnoy E., Gobakken L.R., Aloui F., Cragg S.M., et al., 2019. Durability and protection of timber structures in marine environments in Europe: An overview. Bioresources, 14 (4): 10161-10184. https://doi.org/10.15376/biores.14.4.Treu

Tsinker G. P., 1995. The dock-in-service: Evaluation of load carrying capacity, repair, rehabilitation. Marine Structures Engineering: Specialized Applications, Springer, USA, 1-104. https://doi.org/10.1007/978-1-4615-2081-8

Westin M., Brelid P. L., Nilsson T., Rapp A. O., Dickerson J. P., Lande S., et al., 2016. Marine Borer Resistance of Acetylated and Furfurylated Wood - Results from up to 16 years of Field Exposure. IRG47 annual conference, 15-19/05, Lisbon, Portugal, IRG/WP 16-40756. https://www.irg-wp.com/irgdocs/details.php?3d10b0b4-411a-32f2-b392-0d9aa4644a09

Westin M., Brelid P. L., 2022. Field tests of different tropical wood species in sea water. IRG54 annual conference, 29-05/02-06, Bled, Slovenia, IRG/WP 22-30773. https://irg-wp.com/irgdocs/details.php?61d6cc04-f1b3-d893-b370-26ea38c48614

Williams J. R., Sawyer G. S., Cragg S. M., Simm J., 2005. A questionnaire survey to establish the perceptions of UK specifiers concerning the key material attributes of timer for use in marine and fresh water engineering. Journal of the Institute of Wood Science, 17 (1): 41-50. https://doi.org/10.1179/wsc.2005.17.1.41

Williams J. R., Sawyer G. S., Cragg S. M., Icely J. D., Simm J., Meaden M., et al., 2018. Evaluating less-used timber species for marine construction. Proceedings of the Institution of Civil Engineers - Construction Materials, 171 (4): 134-148. https://doi.org/10.1680/jcoma.15.00065

Zarzyczny K. M., Rius M., Williams S. T., Fenberg P. B., 2024. The ecological and evolutionary consequences of topicalization. Trends in Ecology & Evolution, 39 (3): 267-279. https://doi.org/10.1016/j.tree.2023.10.006

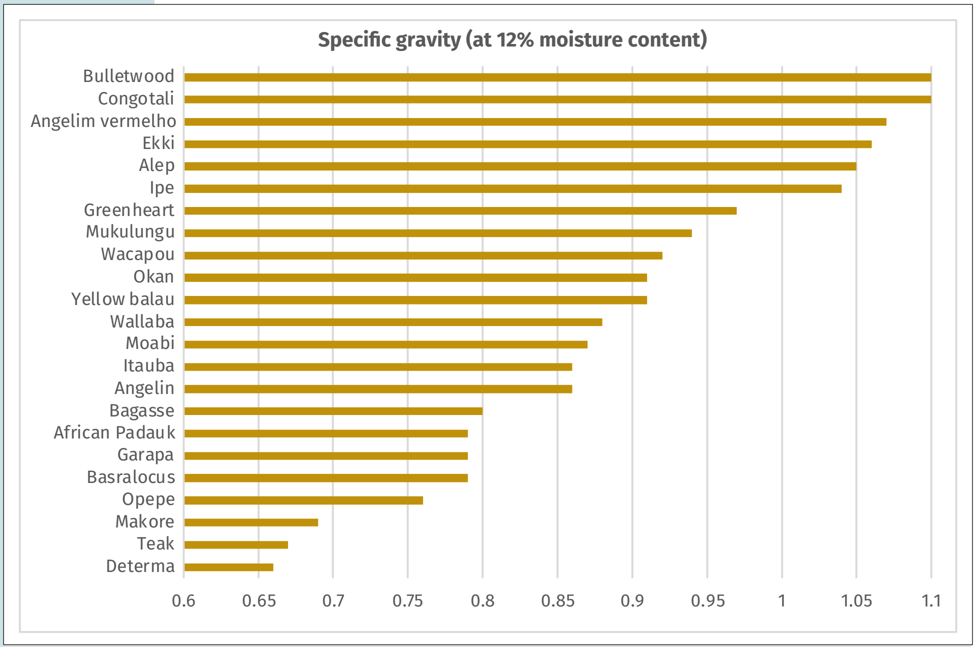

Figure 2.
Distribution of specific gravity of the main commercial woods naturally covering use class 5 (wood immersed in salt water on a regular or permanent basis), source: Tropix (Gérard & Groutel 2020).

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L'ENGAGEMENT EN FAVEUR DE LA GOUVERNANCE DES PAYSAGES RURAUX / RECHERCHE

Local mechanism of engagement in rural landscapes in the Nicaragua-Honduras sentinel landscape: examples of a local farmers' organisation and a multi-actor platform

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Photo 1.
Panoramic view of the Peñas Blanca Natural Reserve.
Photo N. Sepúlveda.

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RÉSUMÉ

Des mécanismes locaux pour promouvoir l'engagement dans la gouvernance des espaces ruraux d'un paysage sentinelle au Nicaragua et Honduras : étude de cas d'une organisation locale d'agriculteurs et d'une plateforme multi-acteurs

Les approches à l'échelle du paysage ont été encouragées comme moyen de relever les défis complexes liés à la gestion des ressources naturelles et au bien-être des utilisateurs des terres et agriculteurs. Cette étude présente deux mécanismes mis en œuvre pour le développement territorial : une plateforme multi-acteurs conçue pour améliorer la gouvernance dans une zone de réserve naturelle (dimension spatiale/géographique) et une coopérative locale devenue réseau d'apprentissage pour aborder les questions d'utilisation des terres et de gestion du paysage. L'étude est basée sur une évaluation de la mise en œuvre d'un outil de planification dans le cadre d'un projet local visant à renforcer la gouvernance du paysage et la coopération autour de la chaîne de valeur dans une réserve de la biosphère au Nicaragua. Nous avons interrogé 403 résidents et 29 membres d'une coopérative cacaoyère afin de recueillir leurs opinions sur l'efficacité des outils et méthodologies appliquées pour assurer d'une part la bonne gestion des ressources naturelles et d'autre part la résilience et le bien-être des cultivateurs de cacao locaux. L'analyse factorielle montre que les habitants de "Peñas Blanca" connaissent la plateforme multi-acteurs qui gère la réserve. En général, ils ont une opinion positive de la plateforme et de sa capacité à concilier les valeurs économiques et culturelles et la conservation des paysages. Depuis quelques années, la coopérative cacaoyère locale est confrontée à une crise financière et organisationnelle, et seul un petit nombre de membres y font appel pour vendre leurs fèves de cacao. Cette situation est due à une baisse de la productivité et de la qualité des fèves de cacao de certains agriculteurs, ce qui a réduit leurs possibilités de vendre leurs fèves à la coopérative. Toutefois, l'accès actuel au capital social et culturel favorise la résilience et la capacité d'adaptation des producteurs de cacao de la région. Ces études de cas démontrent l'efficacité des organisations multisectorielles et communautaires pour l'intégration d'objectifs économiques, écologiques et sociaux dans une région qui favorise la gouvernance paysagère, où les approches sectorielles s'avèrent être des points d'entrée utiles.

Mots-clés : cacao, gouvernance paysagère, outils de planification, plateforme multi-acteurs, zones protégées, territoire, Nicaragua.

ABSTRACT

Local mechanism of engagement in rural landscapes in the Nicaragua-Honduras sentinel landscape: examples of a local farmers' organisation and a multi-actor platform

Landscape approaches have been encouraged as a means of addressing the intricate challenges related to natural resource management and the well-being of land users/farmers. The study presents two mechanisms applied to territory development: first, a multi-stakeholder platform to improve governance in a natural reserve area (space/geographical dimension); second, how a local cooperative can become a learning network and address land-use and landscape management issues. The study evaluates the planning tool interventions of a local project, aiming to strengthen landscape governance and value-chain collaboration in Nicaragua's biosphere reserve. We interviewed 403 residents and 29 cocoa cooperative members to evaluate their view of the tools/methodologies' effectiveness in natural resource management and cocoa farmers' resilience and well-being, respectively. Factorial analysis showed that the people of "Peñas Blanca" were aware of the multi-stakeholder platform managing the reserve. Generally, they had a positive opinion of the platform and its ability to balance economic and cultural values with conservation. The local cocoa cooperative has faced a financial and organisational crisis in recent years, with only a small number of members using the cooperative to sell their cocoa beans. This is due to decreased productivity and quality of the cocoa beans for some individual farmers, which impacts their ability to commercialise the beans with the cooperative. However, current access to social and cultural capital is supporting the resilience and adaptive capacity of the cocoa farmers in the territory. The studied cases provide evidence of the effectiveness of multi-sectoral and community-led organizations in integrating economic, ecological, and social objectives in a territory supporting landscape governance with sectoral approaches as valuable entry points.

Keywords: cocoa, landscape governance, planning tools, multi-stakeholder platform, protected areas, territory, Nicaragua.

RESUMEN

Mecanismos locales para promover el compromiso en la gobernanza de paisajes rurales en el paisaje centinela de Nicaragua-Honduras: ejemplos de organizaciones de agricultores locales y plataformas multiactores

Los enfoques de paisaje se han incentivado como medios para abordar los retos intrincados relacionados con la gestión de recursos naturales y el bienestar de los usuarios de la tierra y agricultores. El estudio describe dos mecanismos aplicados al desarrollo territorial: primero, una plataforma multiactores diseñada para mejorar la gobernanza en un área de reserva natural (aspecto espacial y geográfico); en segundo lugar, cómo una cooperativa local puede convertirse en una red de aprendizaje y abordar problemas de uso de la tierra y de gestión del paisaje. El estudio se basa en una evaluación de los usos de una herramienta de planificación para un proyecto local, que está diseñada para reforzar la gobernanza paisajística y la coloboración en la cadena de valor de la reserva de la biosfera nicaragüense. Entrevistamos a 403 residentes y 29 miembros de una cooperativa cacaotera para evaluar sus opiniones sobre la eficacia de las herramientas y metodologías aplicadas para garantizar la gestión de recursos naturales, por un lado, y la resiliencia y el bienestar entre los productores de cacao locales, por otro lado. El análisis factorial mostró que la gente de Peñas Blanca estaba informada sobre la plataforma multiactores que gestiona la reserva y generalmente tenían una opinión positiva de la plataforma y su capacidad de equilibrar valores económicos y culturales con la conservación. La cooperativa cacaotera local se ha enfrentado a una crisis financiera y organizativa en los últimos años, y solo un pequeño número de sus miembros utilizaba la cooperativa para vender el grano de cacao. Esto es debido a un declive en la productividad y la calidad de su grano de cacao para algunos agricultores individuales, lo que afectó a su capacidad de vender el grano de cacao a la cooperativa. Sin embargo, el acceso actual al capital social y cultural respalda la resiliencia y la capacidad adaptativa de los cultivadores de cacao de la zona. Estos estudios de caso muestran la efectividad de las organizaciones multisectoriales guiadas por la comunidad para integrar objetivos económicos, ecológicos y sociales, en un área que apoya la gobernanza paisajista, donde los enfoques sectoriales actúan como valiosos puntos de entrada.

Palabras clave: cacao, gobernanza paisajista, herramientas de planificación, plataforma multiactores, áreas protegidas, territorio, Nicaragua.

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Introduction

Over the past few decades, the landscape approach, also known as integrated landscape management, has been increasingly advocated as a comprehensive approach for addressing complex social, economic, environmental, and political challenges in the realm of natural resource management (NRM) (Scherr et al. 2012; Ros-Tonen et al. 2013; Reed et al. 2016; Reed et al. 2020b). NRM refers to a specific set of natural resources, aiming to manage competing uses such as agriculture with conservation goals. (Robinson 2019). In landscape research, the focus is on the intersection of natural and human-modified environments (Robinson and Carson 2013).

The term "landscape" has its roots in the Germanic language. It was first documented in the 13th century and is derived from the Dutch word "lantscap" (also spelled "lantscep" and "landscip"), which refers to a portion of land or environment that has been organised by humans and its visual appearance (Antrop 2013; Antrop and Van Eetvelde 2019). Dutch painting introduced its meaning as "scenery" in the 17th century. When it was introduced to the English language, the emphasis was on scenery rather than the territory itself (Antrop 2013).

The various interpretations and meanings assigned to the term "landscape" combined with linguistic interpretations and translations added a lot of confusion to the word. The early stages of landscape research clarified its scientific meaning and concept (Jones 1991; Olwig 1996; Antrop 2005a). However, a universal definition was not reached (Jones 1991; Olwig 1996; Antrop 2005b). A formal definition for landscape is given by the European Landscape Convention, which defines landscape as "an area, as perceived by people, whose character is the result of the action and interaction of natural and/or human factors" (Council of Europe 2000).

To provide specificity and clarity of meaning, an adjective can be added to the term (i.e., cultural landscape, natural, rural landscape). Therefore, the definition of landscape is contingent on the context, the background of users and observers, and the methods and techniques employed to study it (Cosgrove 2003). Landscape research has evolved from its beginning in scientific research in the 18th century, following different trajectories (Antrop 2005a; Antrop 2013).

Landscape ecology introduced a transdisciplinary approach to landscape research, which gave rise to the field of landscape science. Landscape science is considered a meta-discipline, that has evolved through the synergistic application of theories, methods, and knowledge of several scientific disciplines, including agricultural science, forestry science, conservation science, geoscience, biology, social sciences, engineering sciences, and mathematics (Robinson and Carson 2013). Consequently, the landscape concept has become more applied, socially orientated, and less theoretical and academic (Antrop 2013; Antrop and Van Eetvelde 2019). In 2011, landscape emerged as an integrating concept with applications in policy, planning, and management, due to its transdisciplinary and holistic approach (Antrop and Van Eetvelde 2019). For example, researchers have used landscape concepts to understand complex socio-ecological systems and sustainability (Angelstam et al. 2013) and developed frameworks to analyse the complex interactions shaping local rural landscapes (Pinto-Correia and Kristensen 2013).

The landscape approach, as devised by Sayer et al. (2013) in the NMR arena, consists of providing tools and concepts for allocating and managing land to achieve social, economic, and environmental objectives in areas where agriculture, mining, and other productive land uses compete with environmental and biodiversity goals. Sayer et al. (2013) proposed ten summary principles to support the implementation of a landscape approach that emphasises adaptive management, stakeholder involvement, and multiple objectives. Similarly, Scherr et al. (2012) highlighted that to successfully implement landscape approaches, at least four institutional mechanisms are needed: multi-stakeholder planning, supportive landscape governance, resource tenure, and spatially targeted investment in the landscape that supports conservation/environmental objectives.

Landscape governance is related to the general process of steering human-nature interactions in a bounded geographical space (Lockwood et al. 2010). In landscape governance, three types of agents interact (land user managers, public agencies, and local community), shaping territorial (individual decisions) and spatial competence (policy interventions) (Primdahl et al. 2018). Local communities (for example, cooperatives and organisations of civil society interested in maintaining services and benefits from the landscape) can influence the spatial and territorial relationship in landscape governance.

Robinson (2019) emphasised the need to include the views and knowledge of "stakeholders" (mainly landowners/managers and community groups) when analysing landscape and NRM. Other researchers have acknowledged the crucial role of stakeholders in socio-economic development in rural landscapes (Ángel 2010). Similarly, Rana and Chhatre (2017) highlighted the importance of having hybrid forms of governance that involve state/government authorities, communities, and local governments interacting and negotiating socio-environmental aspects of an ecosystem to devise innovative solutions to solve complex problems.

This paper focused on two case studies, framed on sectoral approaches, within distinct geographical spaces, both of which are part of a protected area (PA). The first case study explored how inhabitants perceived the role of a multi-actor platform established to manage a private natural reserve, reflecting the concept of "new institutionalism," here referred to as a means for engagement of a community-based collaborative mechanism, while the second case study examined the perception of the members of a cooperative operating within a global value chain commodity, acting as a learning network and representing an analysis of the organisation within. These case studies are presented as examples of existent mechanisms in a territory, providing the opportunity to assess them as entry points to advance landscape governance and integrated landscape approach for sustainable management. They also shed light on how land users and managers perceived the processes shaping spatial planning embedded in NRM landscape governance. These case studies were also part of CATIE's projects on the climate-smart territories approach in Central America (CATIE 2012; Mendoza Rivarola 2015; Mercado et al. 2017).

Methods

Concepts and evaluation framework

Local community engagement (e.g., cooperatives, local conservation groups) is considered a critical element in landscape governance and management (Primdahl et al. 2018). This study focuses on two sectoral arrangements contributing to local landscape governance in specific territories. The first institutional arrangement is a local multistakeholder platform that governs the access and management of resources in a natural protected area. Multistakeholder engagement platforms are acknowledged as crucial for approaching complex situations and advancing landscape approach and governance (Reed et al. 2020a; Bayala 2023). Multi-stakeholder platforms (MSPs) are defined as "participatory processes that include a wide range of actors in a topic or a landscape, to engage in dialogue, decision-making, and/or implement activities for common (landscape) goals" (CIFOR-ICRAF nd).

The second institutional arrangement is an agricultural cooperative acting as a learning network. A cooperative is defined as "an autonomous association of persons united voluntarily to meet their common economic and social goal as well as aspirations through a jointly owned and democratically owned initiative" (International Cooperative Alliance 1995). Cooperatives offer a means to increase collective actions by facilitating the insertion of smallholder farmers in agri-food value chains, thereby creating opportunities to advocate and motivate their members with tangible economic and social outcomes (Ubandoma 2022; Christian et al. 2024). Therefore, both cases represent some of the arrangements existent in a territory and can be needed as entry points to advance landscape governance and tackle the challenges faced by communities living in complex socio-ecological systems in the agricultural-forest landscape continuum (figure 1).

To analyse the first institutional arrangement, we use the concept of "good governance" to evaluate from the perspective of the land use manager/user the effectiveness of the multi-stakeholder platform in delivering the objectives of the management plan of the PA (socio-economic development and conservation). Good governance is characterised as "participatory, accountable, transparent, responsive, consensus-orientated, effective and efficient, equitable and inclusive, and follows rules of law" (UN Economic and Social Commission for Asia and the Pacific 2003). Governance could be referred to as "the exercise of authority, including the processes, acts, and decisions of a group or entity within a given context (i.e., protected area)" (Tucker 2010), or "the integrity of institutions and processes that govern forests in their countries" (GFI 2009).

Figure 1.
Process supporting landscape governance and spatial planning through two local arrangements.

We applied a questionnaire composed of selected indicators within the eight dimensions of the governance process at the local level proposed by Secco et al. (2014). However, we acknowledge the limitations posed by using this framework, as it did not offer the means to evaluate deeper local participation in the multistakeholder platform, as suggested by other authors (Ruano-Chamorro et al. 2021). The assessed dimensions were: 1) Sustainable glocal development, 2) Efficiency, 3) Effectivity, 4) Participation, 5) Transparency, 6) Accountability, 7) Capacity, and 8) Conscience. In this assessment, the term glocal (i.e., a combination of global and local processes) represents that global and local processes are strictly "intertwined" (Swyngedouw 1997 p. 137; Roudometof 2021). That is, the idea that local projects' performances can positively or negatively affect the society-environment systems globally (Berkes 2008; Secco et al. 2014). In the PA, for example, the decisions on forest cover-tree management on farms in the landscape can influence biodiversity conservation goals (i.e., deforestation, illegal logging) and national commitments on a global scale. In terms of the conscience dimension, in this study, we assessed the view of land users on the role of tree cover change at the farm level in reducing vulnerabilities linked to conditions of uncertainty (i.e., climate change, productivity, water quality).

In each dimension, 4 to 21 questions were included (table I). The questionnaire included 84 questions that used a 5-point Likert scale or yes or no questions. In the Supplementary Material, the statements evaluating each dimension are summarised. The scale used to evaluate the questions/statements was as follows: 1 = Completely disagree, 2 = Not agree, 3 = Undecided/Neutral, 4 = Agree, and 5 = Completely agree. We surveyed 403 residents, randomly selected from the residents of the PA, belonging to 39 communities of the four municipalities ascribed to the PA.

For the second institutional arrangement, a cooperative acting as a learning network and a key player in landscape management, we use the five-capital assessment framework for sustainability (Emery and Flora, 2006) as a vehicle to strengthen the capacity of the cooperative members to deal with climate change and help in the adaptation planning process (Altamirano Tinoco 2012; Rodríguez Cortes and Ospina Rojas 2016).

We performed a non-experimental quantitative evaluation using questionnaires in 2020 to assess, ex-post, the changes that occurred between 2012 and 2020 in the set of the 28 practices proposed in 2012 by Altamirano Tinoco (2012). These practices were designed to enhance the resilience of cocoa farmers and enable the community to plan more effectively, thereby preventing the loss of vital agricultural land uses. Using the information available from a local cocoa project and the results from the evaluation of Altamirano Tinoco, we recreated the initial situation (as of 2012) and then consulted the same cocoa farmers in 2020 to see changes in the practices and indicators perceived by cocoa farmers.

All individuals interviewed for this research have voluntarily agreed to be included in the study and they remain anonymous.

Two examples as case studies and regions

Case Study 1: Peñas Blanca Natural Reserve (PBNR).

In Nicaragua, the national system for natural protected areas (PAs) recognised 76 PAs, which account for 17.6% of the national territory. The Peñas Blanca Natural Reserve is co-managed by the Centre for Understanding for Nature (CEN, by its acronym in Spanish), in coordination with local governments of four municipalities, local organisations, governmental organisations (i.e., the Ministry of Agriculture office, the Ministry of Natural Resources office, and the Forestry National Institute office), and NGOs (Non Government Organisations). Together, these organisations formed a multi-actor platform known as CMC (short for management commission platform). The platform objectives are to conserve, restore, and conduct research in the protected area, as well as support the community in different domains, such as environmental education, support in the formation of local cooperatives, and search for opportunities for young and women. The CEN leads the local platform by working with 1) the municipalities, which support some activities in the reserve such as reforestation, risk management, and road building through their environmental or technical unit; 2) the CAPS (Drinking Water and Sanitation Commissions, CAPS for its acronym in Spanish); and 3) the Environmental Commissions (part of the Family, Community, and Life communal Groups). The CEN has a direct relationship with the local offices of the Ministries and has formed an alliance with MARENA (the Natural Resources Ministry) for the formulation and creation of the PBNR Management Plan, which is the legal instrument recognised to manage the protected area. The PNBR is one of the six nucleus areas of the Bosawas Biosphere Reserve, and its vegetation is characterised by cloud forests (photo 1).

All sustainable activities - defined as the set of actions that align with the ecosystem's potential, restore forest cover and the volume of water sources, eliminate water contaminants from agricultural and livestock activities, and guarantee sufficient income generation for families living in the PNBR and using natural resources - are permitted in the buffer zone and nucleus area of the reserve, as stated in the management plan (Centro de Entendimiento con la Naturaleza (CEN) 2011). MARENA is the local authority that supervises and authorises all the productive activities carried out in the PNBR (Bogarín Bermúdez 2014; Ministerio del Ambiente y los Recursos Naturales 2021).

A series of master´s theses were conducted by students from the CATIE-Graduate School under the Forest, Trees, and Agroforestry (FTA) research program of the CGIAR in the Nicaragua - Honduras Sentinel Landscape (NHSL) initiative (see Sepúlveda et al. 2020 for further information about the Sentinel Landscape initiative). The objectives of these theses were to support the governance and interaction of land managers in the landscape through the development of skills such as multi-stakeholder negotiations and analysis of rules (León Leiva 2014; Rodríguez Cortes and Ospina Rojas 2016) and procedure advising, such as updating the management plan of the PA (Bernales Leiva

Table I.
Statements evaluating the eight dimensions of good governance applied to the multistakeholder platform existent in the natural protected area.

Governance dimension	Statement evaluated	Acronym
Glocal	CMC's formal commitment to sustainability and environmental, social, and economic objectives in the municipality.	S11gLOC
	The best practices are promoted for tourists and other users who visit the reserve.	S12gLOC
	The social impacts of the implementation of actions in the PBNR are favorable for your municipality.	S13gLOC
	Economic development projects are benefiting indigenous peoples in your municipality.	S14gLOC
	There exists a formal commitment to the sustainability and social, environmental, and economic objectives for your municipality and the PBNR.	S15gLOC
	Economic impacts of the projects implemented in the PBNR are positive.	S16gLOC
	Environmental impacts of the projects implemented by the CMC are positives.	S17gLOC
Efficiency	The CMC invests money in updating innovative technological tools to keep the population informed.	S27EFFI
	Residents know the essential aspects of the PBNR very quickly - the CMC informs you promptly about the critical changes in management in your municipality.	S28EFFI
	Implementation deadlines (of projects) are respected.	S29EFFI
Effectiveness	Projects promoted for the conservation of the forest are favorable for the community.	S32EFFE
	Residents have access to information immediately.	S33EFFE
	There exist mechanisms of coordination between CMC and the rest of the organizations in the municipality.	S34EFFE
	(my) The municipality is well represented on the Committees that make decisions regarding forest conservation.	S35EFFE
	Projects meet the objectives of the management plan for which they were designed.	S36EFFE
	CMC effectively manages its relationship with other actors.	S37EFFE
	CMC has high credibility in the territory.	S38EFFE
Participation	Representatives of your municipality have easy access to the CMC.	S41PART
	Your representative informs you of the decisions made in the CMC.	S42PART
	I believe that the CMC is willing to consider recommendations from civil society in general.	S43PART
	(My) demands - opinions are channeled by the representative of the municipality to the CMC.	S44PART
	The CMC handles conflicts appropriately.	S45PART
Transparency	I believe that I can access information on forestry projects and sound environmental practices if required.	S47TRANS
	Residents can give feedback to the representative of your municipality before the CMC without any problem.	S48TRANS
	If residents require information on activities related to forest management, they go to the CMC.	S49TRANS
	There is a flow of information between the municipalities that participate in the CMC.	S50TRANS
Accountability	All the decisions made by the CMC are documented in records.	S51ACCO
	Each member of the CMC has clarity in their role on the committee.	S52ACCO
	CMC has a clear mandate and vision, and there is no duplicity with any other institution/organization in the reserve.	S53ACCO
	The remuneration of CMC members who receive salaries is publicly known.	S54ACCO
	Indicators of the performance of the CMC are clear.	S55ACCO
	The external evaluations of the CMC have been robust to know the areas for improvement.	S56ACCO
Capacity	Members making the decisions in the CMC have the competencies, leadership, and required experience.	S57CAPA
	It is necessary to strengthen the functioning of the CMC (i.e., infrastructure - offices-equipment).	S58CAPA
	Subcommittees are optimal for the CMC to perform properly.	S60CAPA
	I believe that we need other institutions so that they can help in the management of natural resources.	S61CAPA
Conscience	Do you believe that planting trees on my farm helps to improve productivity?	S62CON
	Do you believe that trees favor infiltration and recharge of water sources?	S63CONS
	Do you believe that trees help in reducing the problems of climate change?	S64CONS
	I believe that farmers are the only ones who should plant trees on their farms.	S66CONS
	I believe that coffee growers are the only ones who should plant trees on their farms.	S67CONS
	I believe that the trees on-farm help reduce climate change.	S69CONS
	I have included trees on my farm because my best friends have recommended them to me.	S70CONS
	I always go to a member of the CMC when I need help with which trees to plant.	S71CONS
	Do you believe that trees help in reducing the effects of climate change?	S73CONS
	You consider that the actions promoted by the members of the CMC have influenced my opinion regarding the benefits I receive for planting trees.	S74CONS
	I usually implement on my farm the technical recommendations that CMC members give me.	S75CONS
	I believe that planting trees on the farm is an investment to earn income in the future.	S76CONS
	I believe that planting trees on the farm helps in reducing the effects of climate change.	S77CONS
	Do you consider that the natural regeneration areas are an investment to obtain income in the future?	S78CONS
	Do you believe that natural regeneration areas help water infiltration?	S79CONS

CMC: management commission platform.

and Bloomfield Melgar 2016), all aimed at supporting the CEN and CMC (photo 2). The NHSL initiative did not provide direct incentives to the residents of the PA or support any specific project promoted by the CMC or CEN.

Case Study 2: Building resilience of cocoa farmers and cocoa cultivation in Waslala with the CACAONICA farmer´s organisation case.

CACAONICA was the first cooperative of cocoa farmers in Nicaragua, involved in cocoa cultivation, processing, and exports. In the first half of the last decade, CACAONICA held a privileged position within the cocoa value chain (CATIE 2007; Escobedo 2010). Cooperatives are widely recognised as vehicles for community and rural development in poor territories (Majee and Hoyt 2011; Gutiérrez 2014). Cocoa cultivation is considered a promising crop for livelihood and restoration efforts as it can help stop deforestation. However, cocoa farmers face numerous challenges affecting their capacity to respond to shocks and natural hazards. In 2012, under the Central America Cocoa Project (PCC), a cooperation platform between CACAONICA and CATIE was established. Altamirano Tinoco (2012) identified, proposed, and co-created a set of climate-smart and resilient practices using the community capital assessment framework (see Emery and Flora 2006 for an in-depth review of the framework) to measure the adaptive capacity of cocoa cultivation as a sustainable livelihood. The capital assessment framework allows from a systemic perspective to look at how farmers perceive and face realities and how changes occur in a community (Emery and Flora 2006).

The indicators were built with 37 cocoa farms selected from the 250 cocoa farmers participating in the PCC project. The selection criteria were altitude (range from 200 m asl to 650 m) and previous records on livelihoods measurements. A total of 28 practices were recommended to evaluate resilience and adaptative capacity at the farm level, based on the score of 47 indicators.

Data analysis

For case study 1, the Likert-scale responses were analysed using the Likert package in R (R Core Team 2015) to rank the variables measuring the governance dimensions. A factorial analysis was run using the fa () function to run a model with varimax rotation to transform factors. We set five factors in the model (table II). The factorial analysis allows us to simplify complex data using statistical procedures to explore the underlying patterns or dimensions that explain the relationships between multiple items or variables. In our case, it can show what elements of the governance dimensions of the CMC are recognised by the residents of the PA. For case study 2, descriptive statistics and T-student analyses were run to analyse CACAONICA cocoa farmers' adaptive capacity and resilience changes between the two periods evaluated, according to the perceptions of CACAONICA members. These analyses will shed light on the elements that can further advance landscape governance.

Table II.
Standardised loadings > 0.5 (in bold) of each statement represent the correlation of each statement with a factor based upon the correlation matrix. See the text for the full explanation for each statement.

Governance Dimension	Statement	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
Local development (glocal)[1]	S15gLOC	**0.52**	-0.02	-0.13	-0.13	0.09
	S16gLOC	**0.51**	0.03	-0.03	-0.03	0.15
	S17gLOC	**0.59**	-0.02	-0.17	0.17	0.06
Effectiveness	S32EFFE	0.17	0.08	0.1	-0.03	**0.56**
	S34EFFE	**0.54**	-0.06	0.02	-0.11	0.11
	S35EFFE	**0.6**	-0.16	0.01	0.11	-0.11
	S37EFFE	**0.54**	-0.06	0.21	-0.04	0.1
	S38EFFE	**0.65**	-0.08	0.11	0.05	-0.19
Participation	S42PART	0.11	-0.21	**0.56**	0.16	0.06
Accountability	S51ACCO	**0.53**	0.11	0.02	-0.02	0.06
	S52ACCO	**0.59**	0.14	0.01	-0.29	0
	S53ACCO	**0.51**	0.25	-0.01	-0.16	0.16
	S55ACCO	**0.5**	0.11	0.08	-0.25	0.04
Capacity	S57CAPA	**0.52**	0.03	0.07	-0.08	0.02
	S58CAPA	0.03	-0.04	0.02	-0.07	**0.59**
	S59CAPA	0.08	0.05	0.17	**0.51**	0.22
	S60CAPA	0.03	0.15	0.04	0.16	**0.51**
	S61CAPA	-0.06	0.12	-0.01	-0.01	**0.63**
Conscience	S63CONS	0.11	**0.65**	0.07	0.24	-0.38
	S64CONS	-0.05	**0.73**	0.18	0.08	-0.23
	S66CONS	0.18	-0.17	0.05	**-0.63**	0.04
	S67CONS	0.2	-0.17	0.07	**-0.67**	0.03
	S69CONS	-0.04	**0.81**	0	-0.02	0.14
	S70CONS	-0.14	0.2	**0.53**	-0.08	-0.06
	S71CONS	0.08	0.13	**0.61**	-0.04	-0.2
	S73CONS	-0.03	**0.77**	-0.04	0.03	0.12
	S74CONS	0.06	0.06	0.45	-0.07	0.18
	S75CONS	-0.05	0.12	**0.71**	-0.16	0.11
	S76CONS	0.03	0.32	-0.03	0.01	0.22
	S77CONS	0.07	**0.75**	-0.07	-0.03	0.21
	S78CONS	0	0.27	0.15	0.23	0.38
	S79CONS	0.29	0.44	-0.18	0.19	0.27
	S80CONS	0.05	0.12	-0.15	0.25	0.14

[1] = glocal (i.e., a combination of global and local processes. Global and local processes being strictly "intertwined" (Swyngedouw, 1997 p. 137).

Results

Case Study 1: Governance of the Peñas Blanca Natural Reserve as seen by local users

Forty-seven per cent of the population interviewed were females, and 53% were males. On average, the age of the interviewees was 40 years old (median 38 years, sd = 15.7 years). Forty-four per cent of the participants live in the buffer zone, 20% in the nucleus zone, and the rest (36%) mentioned that they were outside the limits of the PA. Regarding education, only 8% of the interviewees were illiterate. Fifty-one per cent of the interviewed population had completed at least one school year of primary school, and 20% had completed at least one year of secondary school. Eight per cent of the participants took part in a state-promoted literacy program. Six per cent reported that they had completed secondary school, and only 7% of the interviewees had completed a university degree.

Governance indicators characterising the multi-actor platform (CMC) as perceived by local users.

The statements that scored high in factor 1 (loading > 0.5) were related to the governance dimensions of glocal (a combination of global and local processes) with three statements, effectiveness (four statements), accountability (four statements), and capacity (one statement). These statements referred to 1) members of the CMC having a clear understanding of their roles in the platform (S52ACCO); 2) the CMC having high credibility in the territory (S38EFFE); and 3) the existence of a mechanism of coordination between the CMC and the rest of organisations existent in the territory (S34EFFE). Other high-ranking statements are that the CMC platform effectively manages its relationship with other actors (S37EFFE), the CMC has a clear mandate and vision, and there is no duplicity with any other institution/organisation (S53ACCO) in the PA.

Other items that have a high load on factor 1 were: 1) the existence of a formal commitment to the sustainability and social, environmental, and economic objectives for the municipality and the PBNR (S15gLOC); 2) projects promoted/implemented by the CMC have positive environmental (S17gLOC) and economic (S16gLOC) outcomes. Therefore, factor 1 refers to the CMC's credibility, existing coordination tools, and CMC's ability to promote economic and environmental benefits for the communities.

In factor 2, the statements with a high load were the statements associated with the users' perspectives on trees within the conscience governance dimension. These statements include beliefs such as the recognition of trees' ability to improve infiltration rates and water recharge (S63CONS), the perception that trees (in a general sense) contribute to mitigating the problems caused by climate change (S64CONS), and the acknowledgement of the role of trees on farms in reducing climate change (S69CONS) and its effect (S73CONS), and the belief that planting trees on one's farm helps to fight against climate change (S77CONS). Overall, this factor reflects a positive outlook on the role of trees in addressing climate change, promoting productivity, and managing water resources.

In factor 3, the statements with a high load were the statements related to the dimension of participation (one statement) and conscience (three statements). The statement related to participation asks whether the representative informs users/residents of the PNBR of the decisions made in the CMC (S42PART). The remaining three statements relate to the conscience dimension, focussing on users/residents' decisions on tree planting (S70CONS and S71CONS) and whether residents typically implement the technical recommendations given by the CMC on their farms (S75CONS).

Factor 4 comprised three statements with the highest loadings. Two of these statements measured respondents' perceptions of who should be responsible for planting trees on their farms. The loadings for these statements were negative, indicating disagreement among the respondents regarding the belief that only coffee growers (S67CONS) or that only ranchers (S66CONS) should plant trees on their farms. The third statement was related to whether the CMC organises ongoing training meetings in which residents can participate (S59CAPA).

Factor 5 comprised four elements with higher loadings that include statements measuring indicators of the capacity and effectiveness dimension. The statements referred to respondents believing other institutions are needed to help manage natural resources (S61CAPA) and that it is necessary to strengthen the functioning of the CMC through equipment, allowances, and other means (S58CAPA). Additionally, subcommittees are considered optimal for the CMC to perform appropriately (S60CAPA). Finally, the respondents view projects promoted for the conservation of forests as positive (S32EFFE). Overall, this factor indicates that the respondents believe in the importance of including other actors influencing the PNBR and the need for external support to strengthen the CMC.

CMC performance using Likert-scale analysis.

The residents of the PBNR believe that the CMC is committed to the sustainability and socio-economic development of their municipalities in managing the reserve (S11gLOC, 71.2% agreement). They also believe that the implementation of activities delivers positive social impacts for their territories (S13gLOC, 81.5% agreement). However, only 30% of the residents interviewed knew that there was a formal arrangement for managing the PNBR when asked about who oversees the reserve management. Furthermore, 90% of the interviewees were not aware of the annual sustainability reports generated by the multi-actor platform co-managing the PBNR. Additionally, the majority of residents are not aware of the financial mechanisms existent to support the sustainability of the PBNR.

Regarding the efficiency dimension, the respondents mentioned that the multi-actor platform (CMC) does not inform them promptly about essential changes in the management regime of the PBNR. Furthermore, they reported not knowing the crucial aspects of the PNBR co-management plan (S28EFFI, 53% of responses) (Supplementary material, Appendix A).

Photo 2.
Offices of the municipal environmental commission and the environmental and natural resources ministry in Waslala, Nicaragua.
Photo N. Sepúlveda.

In terms of effectiveness, 89% of the residents agreed that "implemented projects" seemed optimistic for forest conservation (S32EFFE, 89% of agreement). They also believed that there are coordination mechanisms between CMC and the local organisations (S34EFFE, 62% of agreement). Regarding the representation of their municipalities in the committees that make decisions about forest conservation (S35EFFE), 47% of the residents agreed that their municipalities are well represented in the committees, 25% showed neutrality, and 28% believed that local authorities are not well represented in the decision-making process (S35EFFE). Forty-one per cent of the respondents agreed that CMC has credibility in the territory (S38EFFE), and thirty-six per cent of the residents disagree with this statement.

Regarding participation, there was a high percentage of neutral responses in the evaluated indicators (Appendix A). In terms of transparency, 68% of respondents agreed that they could access information about current forestry and environmental good practices projects (S47TRANS) if they needed to. Additionally, 50% agreed that they could provide feedback to the CMC through their representatives (S48TRANS). However, 49% of participants indicated that they do not approach the CMC to request information related to forest management activities (S49TRANS).

Regarding accountability of the CMC, most indicators received a high percentage of neutrality and negative views from the interviewees. For instance, residents do not know if the decisions made by the CMC are documented in a registry (41% of the respondents) or if each member of the CMC has a specific role (S52ACCO, 46% of the responses). Additionally, 59% of the respondents concurred that there is no public information about the salaries of the CMC members (S54ACCO), and 35% neither agreed nor disagreed with this statement.

In terms of capacity, 90% of the respondents agreed that other organisations/institutions are needed to aid in managing natural resources (S61CAPA). Additionally, 85% of the respondents agreed that it is necessary to strengthen the functioning of the CMC, with only 3% showing disagreement with this statement (S59CAPA).

The respondents also believed that sub-committees are the best instrument for the CMC platform to perform adequately (S60CAPA, 79% of agreement), 16% of the participants gave no opinion, and the remaining 5% showed disagreement with the statement. Furthermore, 52% of the respondents agreed that the decision-makers of the CMC have the leadership, experience, and abilities required (S57CAPA).

Regarding indicators measuring conscience, there was a 99% agreement among respondents regarding the positive role of trees in climate change mitigation and climate effects regulation (S64CONS and S73CONS) and that trees have a positive effect at the farm level related to climate change (S69CONS). Additionally, 98% of the respondents agreed that planting trees on farms helps to reduce the effects of climate change (S77CONS) and increases the productivity of the farm (S62CONS). Furthermore, 94% of the respondents believed that planting trees on farms is an investment to obtain future incomes (S76CONS) and agreed that trees favour water infiltration and water recharge (S63CONS). However, a high percentage of disagreement was mentioned regarding CMC and dwellers' behaviour. For example, 42% of the respondents said that their beliefs about tree benefits had not been influenced by the actions implemented by the members of the CMC (S74CONS), whereas 45% mentioned that the CMC activities had influenced their beliefs. Likewise, 56% of the respondents indicated that they do not implement on their farms the technical recommendations received by the CMC members, whereas 45% agreed they implement the advice given by the CMC members. Regarding tree planting responsibility, a high percentage of agreement was reported (90% and 98%, respectively) among the respondents, indicating that it is not the responsibility of only ranchers (S66CONS) or coffee farmers (S67CONS) to plant trees, it is a shared responsibility. However, the respondents agreed in the importance of tree planting in their farms.

Tree cover changes on farms of the residents of the PNBR as reported by landowners.

Users of the PNBR were also asked about the number of trees managed on their agricultural lands. Landowners reported an increase in tree numbers in agricultural lands when we compared the number of trees registered in 2013 and 2020, and this difference was statistically significant ($t = -1.6469$, $df = 804$, $p < 0.005$). The positive changes ranged from 5.6% to 2757% and were reported by 86% of the respondents. Less than 1% of the respondents did not have trees in their agricultural lands in 2013. Four per cent of the residents retained the same number of trees in 2013 and 2020 in their agricultural lands. Five per cent of the interviewed reduced tree cover in their agricultural lands, with losses ranging from 7.7% to 98% of the total of individuals reported in 2013. Furthermore, 5% of the residents did not change their perspectives about trees as they did not include trees in their agricultural lands in 2020 or 2013.

Regarding existing natural regeneration areas on farms, 72% of the interviewees reported they do not have natural regeneration areas on their property. Two interviewees reported a decrease in natural regeneration areas (-16% and 100%). Additionally, 11% of the respondents reported the same natural regeneration area in 2013 and 2020. Only 8% of the interviewed reported an increase in size under natural regeneration areas compared to 2013, and 6% reported having natural regeneration areas compared to 2013.

Case Study 2: Resilient cocoa farmers through local-led organisations

Socio-economic characteristics

A total of 29 cocoa farmers participated in the assessment, 80% of the total participants of the 2012 study. Farmers were 58 years old on average. Most of the interviewees were men (96%), and only one woman was the head of the household. Eighty-three per cent were identified as farm owners, 10% were identified as owners and administrators, and the remaining 7% as "other" (i.e., son owners). On average, 5.7 persons live in a household. Participants reported an average of 41 years of agricultural experience, with 23 years on average involving cocoa cultivation (table III).

Despite a high literacy rate of 81% among the interviewed cooperative members, only 17% had completed primary school, 3% had completed secondary school, and 3% had obtained a technical degree. The remaining 19% either did not know or did not provide an answer.

Natural and built capital dimensions: changes in farm areas, cocoa cultivated areas, tree cover in cocoa, and use of cocoa AFS sub products between 2012 and 2020.

Interviewees reported a decline in the number of tree individuals in the shade canopy component intercropped with cocoa between 2012 and 2020 (table IV). However, only the number of individuals reported for bananas was statistically different between years ($p < 0.05$). There was a slight increase in the farm area and in the cocoa area between 2012 and 2020, but this difference was not statistically different. There was also an increase in cocoa plants cultivated per hectare.

Forty-five per cent of the farmers had diversified their farms mainly by including fruit and service trees in their cocoa plots and cultivating staple crops (maize and beans) in adjacent fields. The remaining 65% mentioned they did not diversify their cocoa farm in the last five years. When asked about the use of agroforestry products, there was an increase in the number of products used from the cocoa AFS for general well-being, household self-consumption, and feeding animals compared to the numbers of farmers reporting the use of agroforestry products in 2012 (table V).

Table III.
Socioeconomic characteristics of the cocoa farmers in Waslala, Nicaragua.

Variables	Value
Family Members (#)	5.7 (± 3.19)
Only sons/daughters	3.34 (± 2.88)
Years of experience in agriculture	41.83 (± 15.99)
Years of experience in cocoa cultivation	23.10 (± 8.47)
Years of membership with CACAONICA	17 (5.4)

Table IV.
Changes in the area and shade composition of cocoa agroforestry system of Waslala, Nicaragua.

Indicators	Value 2012	Value 2020	Change	*p* -value
Farm area (ha)	18.5	18.7	↑	0.9758
Cacao area (ha)	2.48	3.4	↑	0.1851
Cocoa trees (# individuals/ha)	646.8	709.9	↑	0.3484
Musaceae intercropped (# individuals/ha)	161.7	103.08	↓	0.08968
Shade trees (# individuals/ha)	73	65.5	↓	0.7247

p-value: statistical significance

Table V.
Responses of changes in the use of cocoa agroforestry systems products between 2012 and 2020 of Waslala, Nicaragua.

Indicators	2012*	2020*	% Change
Use of products from the companion trees/crops from the cocoa AFS			
Greater than five products	8	16	100.0
Less than five products	21	13	-38.1
Use of products from the companion trees/crops from the cocoa AFS for self-consumption			
Greater than five products	8	14	75.0
Less than five products	20	15	-25.0
Use of products from the companion trees/crops from the cocoa AFS for animal feeding			
Greater than three products	3	6	100.0
Less than three products	21	17	-19.0

*Values correspond to the number of farmers answering which use category is linked to a specific year.

Tree cover recognition

Thirty-eight per cent of the respondents did not report natural regeneration areas on their farms between 2012 and 2020. Only one cocoa farmer reported a decrease in the existent area under fallow (natural regeneration) in its property of 35% compared to the 2012 area. Twenty-four of the respondents (83%) maintained the same area under natural regeneration in their farms in 2012 and 2020. Ten per cent of the interviewed reported in 2020 that they now manage natural regeneration areas in their farms compared to 2012. Thirty-one per cent of cocoa farmers increased their natural regeneration area; the changes in areas ranged between 33% and 102% compared to 2012.

Based on the responses of cocoa farmers, there appears to be sufficient water from rivers and streams that cross their properties, so it is not common to build water reservoirs or other infrastructure to store rainwater. Only four farmers (14%) reported having infrastructure for water capture on their properties.

Financial capital: changes between 2012 and 2020

Fifty-five per cent of farmers reported a decrease in cocoa production for 2020 compared to 2012, with an average reduction of 45% in yields of dry cocoa beans (from 13.7 qq/ha in 2012 to 7.6 qq/ha in 2020, p = 0.04182; 1 qq equivalent to 1 bag of 46 kg). The negative changes ranged from 0.7% to 100% (total loss). The main reasons for these losses were attributed to weather factors (i.e., too much rain affecting flowering and fruit production), pests, and diseases (Moniliasis), ageing cocoa plantations, poor management practices, abandonment of cocoa plantations, and renovation of old cocoa plantations. However, 28% of farmers reported an increase in cocoa production, ranging from 11% to 76%, mainly due to good management practices (such as pruning of cocoa plants) and new plantations entering the production stage.

Regarding income generated from cocoa sales, 45% of farmers reported a decrease in revenue compared to 2012, with losses ranging from 8% to 80% per hectare per year. This decline was attributed to lower cocoa yields and prices in the local market for non-fermented cocoa. However, 48% of farmers reported an increase in income from cocoa sales, ranging from 3% to 107% compared to 2012. This increase was mainly due to higher global prices (43% of respondents) and certification (57% of respondents).

Interviewees reported a wide range of incomes from cocoa sales per hectare per year in 2012, ranging from USD 200 to USD 3500. The reported prices for cocoa beans in the national market in 2012 were USD 3.9/kg for certified cocoa and USD 2.2/kg for conventional-fermented cocoa. In 2020, reported incomes from cocoa sales per hectare per year ranged from USD 73 to USD 1575. The reported prices paid for cocoa beans in 2020 were between USD 2.8-3.1/kg for certified cocoa, USD 2.5/kg for conventional-fermented cocoa, and USD 1.8/kg for dry-non-fermented cocoa.

In terms of additional income from the sale of the produce from trees/crops associated with the cocoa AFS, only 17% of the farmers reported 2012 income from this activity. The income per ha/year was between USD 20 and USD 100/ha/year. In 2020, only 14% of the farmers sold any products from the companion trees/crops, and the income provided ranged from USD 30/ha/year to USD 900/ha/year. There was a decrease in the number of farmers reporting consumption of products from the cocoa AFS to reduce expenses (a reduction of 29%).

Cocoa beans are typically transported from the communities to the municipality of Waslala via public transport, such as trucks and buses. The average distance reported by farmers to the nearest market (cooperative/intermediaries) is 12.99 km (±14.21 km), which takes around one hour (± 53.6 minutes) to travel from their farm. Currently, there has been no negotiation between CACAONICA and transport cooperatives regarding the transportation of cocoa beans to improve the service.

The social and cultural capital

According to table VI, 62% of cocoa farmers are currently members of CACAONICA, while 38% (11 farmers) have left the cooperative. Of those who left, four farmers have joined other cocoa cooperatives. The reasons cited for leaving CACAONICA include delayed payments, mismanagement of funds by the board of directors, and payments being made in-kind rather than in cash. Some farmers also stopped contributing monetarily to the cooperative, while others simply wanted a fresh start in other organizations. Currently, only 38% of cocoa farmers are actively involved with the cooperative, while 56% no longer maintain a relationship with CACAONICA either because they are no longer members or are not interested in cooperative activities.

According to the survey results, only 24% of the respondents sell their cocoa production to CACAONICA, while the remaining 76% sell their produce in local markets, intermediaries, or other local cooperatives. The reasons cited for not selling their cocoa to CACAONICA include no longer being cooperative members, the cooperative not having funds to pay farmers, and a preference for selling in the local market due to low cocoa quality.

Regarding training and capacity building, 79% of the farmers responded that they have participated in training events; on average, a farmer participated in 1.9 events per year between 2012 and 2020.

Human capital dimension

Twenty-one farmers (71%) mentioned participating in Field School (FS) programs between 2012 and 2020, with one farmer participating in up to nine events/sessions between 2012 and 2019. The farmers who participated in FS have put into practice what they learnt in the sessions, mainly to increase cocoa productivity. Additionally, half of the farmers reported that they had received technical assistance provided by the cooperative or projects, with an average of 2.7 visits per year.

Table VI.
Responses of cocoa farmers (number of farmers) regarding cooperative membership and educative program broadcasting.

Indicators	Yes	No
Still a member of CACAONICA (2012-2020)	18	11
Actively involved with the cooperative between 2012-2020	9	20
Between 2012-2020 farmers only sell cocoa beans to CACAONICA	7	22

Family labour in cocoa production.

Ten farmers (34%) indicated an increase in family labour to produce cocoa. This increase in labour was due to: 1) an increase in cocoa area; 2) better management/increase in yields; and 3) sons/daughters have come to working age. While seven cocoa farmers (24%) indicated that the family labour decreased because sons/daughters have moved, there was low interest in cocoa cultivation, elder/medical reasons, and less work in the cocoa plot. However, eleven cocoa farmers (38%) indicated that family labour was the same between 2012 and 2020. One farmer said he abandoned cocoa cultivation.

Discussion

In our study, we presented two types of analysis to demonstrate the influence of existing institutional arrangements on landscape governance from the spatial planning perspective. Specifically, we examined farmer and PA residents' opinions on the functioning of a multistakeholder platform and the contribution of a cooperative in building farmers' resilience aimed at coherent and coordinated decision-making within a bounded geography (Münter and Osterhage 2018). This was exemplified by the hybrid governance model, which involved the mobilisation of civil society, public offices, and the engagement of municipalities in the local land use planning. According to the results, this engagement model facilitated a collaborative process, a key principle towards landscape governance (Ros-Tonen et al. 2014). Additionally, we explored the strengthening process of a local organisation aimed at enhancing the social learning process and positively impacting the livelihoods of small cocoa farmers. This process also aimed to improve the member organisation's preparedness for changing climate conditions. Both study cases showcased the opportunities to increase awareness of the actors and entities in a bounded geography of how the multiple interests and uses influence decisions in a territory.

These stakeholders and the tools they use (i.e., management plan, cooperative engagement-farm planning) influence the landscape attributes, especially regarding land cover and land use configuration. Land users/managers (inhabitants) of the PNBR have great regard for the local platform in charge of the nexus between conservation, policies, and social and economic development of the territory. They believe the CMC has credibility and enough coordination mechanisms to work/engage with other organisations and institutions working in the PNBR. These features are key in landscape governance as decision-making networks (social actors) are diverse and continuously changing (Beunen and Opdam 2011). These findings are consistent with other scholars and practitioners' reports on the important role of multi-actor platforms as a mechanism of dialogue, concerted actions, and decision-making to address issues related to the management of natural resources or meet the needs of the communities living in a territory (Larson and Sarmiento Barletti 2020).

By involving all relevant actors in decision-making processes, it is possible to achieve sustainable outcomes that benefit both conservation goals and the people living in the area. For example, in Central Mexico, it was demonstrated the importance of participatory multi-actor engagement in achieving consensus and reconciling the goals of a PA with the needs of local communities (Caro-Borrero et al. 2020). In this case, the PA was created to protect the forest and aquatic resources. Water management was the common ground to reconcile the goals of the PA and the communities living in the PA, as some communities were facing water scarcity. Another key feature to advance the landscape approach (Sayer et al. 2013)

To facilitate effective integration and collaboration among the diverse actors involved, collaborative tools such as multi-level, multi-sectoral, and multi-organisational partnerships are implemented (Lockwood et al. 2010). Sarmiento Barletti et al. (2020) conducted a study to examine the effectiveness of multi-stakeholder forums (MSF) for sustainable land use management. Their findings indicate that the engagement of implementers and their willingness to learn from and listen to stakeholders is crucial. This requires understanding of the existing patterns of relationships among stakeholders and institutions and their power relations. In the PNBR, the CMC has been the platform for reconciling biodiversity conservation, ecological integrity, and socioeconomic development of the territory. As was shown in the analysis of good governance, the residents have agreed, in general, on the good intentions of the platform in bringing socio-ecological benefits to the communities.

Studies carried out by CATIE in the PA have shown that the residents and municipalities embedded in the buffer and area of influence of the PNBR recognised a plethora of environmental services provided by the PA, especially those associated with water provision, hydroelectric, non-forest and forest products, and crop production (see Bogarín Bermúdez 2014). Similarly, in our study, land users/managers recognised the positive role of trees in productivity, fighting climate change, and income generation. Therefore, these individuals reported an increase in tree cover on farms between 2012 and 2020. In the Paraíba Valley (Brazil), societal engagement and environmental policies (command and control) triggered forest/tree recovery in the region (Silva et al. 2017).

Cooperatives as a place-based approach and self-governance form of collaboration are recognised mechanisms that can further advance sustainability and adapt farming practices to restore and improve their endogenous resource base (Swagemakers et al. 2019). In our case, the cooperative CACAONICA has been involved in various initiatives aimed at strengthening its organisational, productive, processing, and commercial position in the cacao value chain of Nicaragua (CATIE 2007; Montoya et al. 2013). These efforts have been undertaken to improve the well-being of cocoa farmers in the region, who rely heavily on cocoa farming for their livelihoods. According to previous studies, cocoa farms in Waslala provide 40% of the total income to cocoa families (CATIE 2010). Local organisations, such as CACAONICA, have been identified as a key factor in strengthening farmers' livelihoods and reducing the negative impact of vulnerability factors, such as droughts, price instability, and social-political conflicts (Abruzzese et al. 2005). Although, according to our results, more than half of the cocoa farmers interviewed are members of CACAONICA, only a quarter of them sell their cocoa beans through the cooperative. Furthermore, there has been a decline in cocoa production and income, indicators evaluated as a proxy of financial resilience. This could be due to most farmers selling their cocoa beans in the local market through intermediaries rather than directly to the cooperative, endogenous factors affecting the performance of the cooperative, and the institutional arrangements maintained by the cooperative with their members, providers, and the main buyers (Montoya Zumaeta 2009).

We found a positive trend of farmers in managing natural resources on their farms. Yet, it has not translated into better financial status, probably because there is no alignment with processes outside the farm and the cooperative. Thus, there is still low reporting on the commercialisation of agroforestry products (trees/crops associated with cocoa) to generate income. Cocoa farmers recognise the value of trees in their plots; nevertheless, this recognition is not associated with having more trees integrated with cocoa plots or managing more natural regeneration areas in their properties, indicating that other factors are influencing tree cover change at the farm level (used here as a proxy of better adaptive capacity).

Our second institutional arrangement provided insight into how local self-governance mechanisms can enhance resilience and farmers' practices, however, well-implemented and organised cooperatives are needed to realise the full potential of this collaboration for advancing landscape management approaches.

Conclusion

The case studies presented evidence of the effectiveness of landscape governance as seen by local land users through the support of existing arrangements in a territory. The multi-stakeholder platform and agricultural cooperatives (i.e., as part of the learning process in a region) were catalysers for integrating new concepts/approaches in the territory and advancing sustainability issues and landscape decisions with stakeholders and local users. However, engaging with farmers' organisations is a double-edged sword, as cooperatives can lose their position, power, and influence in a territory and negatively affect their associates and their capacity to respond to stresses and shocks in the long term. Overall, our study contributes to the understanding of governance and social arrangements in landscape management. It emphasises the importance of engaging stakeholders and other actors of interest involved in shaping landscape structure, and different institutional arrangements are needed (i.e., multi-actor platforms and cooperatives) to achieve sustainable landscape management outcomes.

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Data availability statement

The data that supports the findings of this study are available upon request to the corresponding author. The data are not publicly available for privacy reasons.

References

Abruzzese R., Stoian D., Somarriba E., 2005. Estrategias de vida de los productores emprendedores y desarrollo empresarial rural en el Alto Beni, Bolivia. Agroforestería en las Américas, 43-44: 27-31. https://repositorio.catie.ac.cr/handle/11554/6242

Altamirano Tinoco M. A., 2012. Propuestas de adaptación de la producción de cacao en Waslala, Nicaragua ante el cambio climático. Magister Scientiae. CATIE, Turrialba, Costa Rica. https://repositorio.catie.ac.cr/handle/11554/5476

Ángel J. E. P., 2010. Manejo de stakeholders como estrategia para la administración de proyectos de desarrollo en territorios rurales. Agronomía Colombiana, 28: 491-499. http://www.scielo.org.co/scielo.php?script=sci_arttext&pid=S0120-99652010000300016

Angelstam P., Grodzynskyi M., Andersson K., Axelsson R., Elbakidze M., Khoroshev A., et al., 2013. Measurement, collaborative learning and research for sustainable use of ecosystem services: landscape concepts and Europe as laboratory. Ambio, 42: 129-145. https://link.springer.com/content/pdf/10.1007/s13280-012-0368-0.pdf

Antrop M., 2005a. From holistic landscape synthesis to transdisciplinary landscape management. In: Tress B., Tress G., Fry G., Opdam P. (Eds.), From Landscape Research to Landscape Planning: Aspects of Integration, Education and Application. Springer Science+Business Media, Wageningen, 27-50. https://library.wur.nl/ojs/index.php/frontis/article/view/1098

Antrop M., 2005b. Why landscapes of the past are important for the future. Landscape and Urban Planning, 70: 21-34. https://doi.org/10.1016/j.landurbplan.2003.10.002

Antrop M., 2013. A brief history of landscape research. In: Howard P., Thompson I., Waterton E. (Eds.), The Routledge Companion to Landscape Studies. Routledge, New York, NY, 12-22. https://www.natur.cuni.cz/geografie/socialni-geografie-a-regionalni-rozvoj/studium/doktorske-studium/kolokvium/kolokvium-2013-2014-materialy/2013-antrop-2013.pdf

Antrop M., Van Eetvelde V., 2019. Territory and/or Scenery: Concepts and Prospects of Western Landscape Research. In: Mueller L., Eulenstein F. (Eds.), Current Trends in Landscape Research. Springer International Publishing, Cham, 3-39. https://link.springer.com/chapter/10.1007/978-3-030-30069-2_1

Bayala E. R. C., 2023. Stakeholder Perceptions on Landscape Governance in Northern Ghana: A Q-Study to Identify Common Concern Entry Points for Integrated Landscape Approaches. Environmental Management, 74: 31-51. https://link.springer.com/article/10.1007/s00267-023-01881-2

Berkes, F., 2008. Commons in a Multi-level World. International Journal of the Commons, 2: 1-6. https://www.jstor.org/stable/26522987

Bernales Leiva I., Bloomfield Melgar H., 2016. Propuesta metodológica bajo el enfoque de bienestar humano y cambio climático para la elaboración de Planes de Manejo de las Áreas Protegidas de Nicaragua: Estudio de caso Plan de Manejo de la Reserva Natural Macizo de Peñas Blancas, Nicaragua. Master en Practica de la Conservación de Biodiversidad. CATIE, Turrialba, Costa Rica, 282 p. https://repositorio.catie.ac.cr/handle/11554/8685

Beunen R., Opdam P., 2011. When landscape planning becomes landscape governance, what happens to the science? Landscape and Urban Planning, 100: 324-326. https://www.sciencedirect.com/science/article/abs/pii/S0169204611000557

Bogarín Bermúdez N., 2014. Servicios ecosistémicos reconocidos por los habitantes de la zona de amortiguamiento del Macizo Peñas Blancas, en el territorio Centro Norte de Nicaragua. Master en Práctica de la Conservación de la Biodiversidad. CATIE, Turrialba, Costa Rica, 69 p. https://repositorio.catie.ac.cr/handle/11554/7127

Caro-Borrero A., Carmona-Jiménez J., Figueroa F., 2020. Water resources conservation and rural livelihoods in protected areas of central Mexico. Journal of Rural Studies, 78: 12-24. https://doi.org/10.1016/j.jrurstud.2020.05.008

CATIE, 2007. Competitividad y ambiente en los territorios cacaoteros de Centroamerica. Documento del Proyecto. CATIE-PCC, Turrialba, Costa Rica, 181 p. https://repositorio.catie.ac.cr/handle/11554/9205

CATIE, 2010. El cacaotal mejorado. Guía del facilitador. CATIE, Turrialba, Costa Rica, 32 p. https://repositorio.catie.ac.cr/handle/11554/1532

CATIE, 2012. Construyendo territorios climáticamente inteligentes: Informe anual 2011. Serie institucional. Informe anual no. 32. CATIE, Turrialba, Costa Rica, 36 p. https://repositorio.catie.ac.cr/bitstream/handle/11554/8151/Construyendo_territorios_climaticamente_inteligentes.pdf?sequence=1&isAllowed=y

Centro de Entendimiento con la Naturaleza (CEN), 2011. Plan de Manejo de la Reserva Natural Macizo de Peñas Blancas. Reserva de la Biosfera Bosawas. In: The Natural Conservancy (TNC), cooperativas, organizaciones, propietarios privados y municipalidades del Macizo de Peñas Blancas (Ed.). CEN, 75 p. https://www.renida.net.ni/renida/marena/RENP01M665na.pdf

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Appendix A.

Table 1A.
Responses (in percentage) of the residents (n = 403) of The Peñas Blanca natural reserve around statements (indicators) evaluating governance performance of the CMC platform.

Governance dimension	Statements	Completely disagree	Not agree	Undecided/ Neutral	Agree	Completely agree
glocal	S11gLOC	1.0	8.7	16.4	64.3	9.7
	S12gLOC	0.5	12.4	32.8	52.4	2.0
	S13gLOC	0.0	5.7	11.7	**76.4**	6.2
	S14gLOC	2.7	10.9	40.9	43.7	1.7
	S15gLOC	2.2	10.4	17.9	**66**	**3.5**
	S16gLOC	2.2	7.7	19.1	**67.7**	**3.2**
	S17gLOC	0.0	6.7	25.3	**64.5**	**3.5**
Efficiency	S27EFFI	2.2	19.1	34.7	41.7	2.2
	S28EFFI	**5.7**	**53.3**	22.3	18.1	0.5
	S29EFFI	3.5	19.4	45.4	31	0.7
Effectiveness	S32EFFE	0.2	2.0	6.5	**70.2**	**21.1**
	S33EFFE	2.2	49.9	17.4	29.5	1.0
	S34EFFE	2.2	10.9	25.3	57.8	3.7
	S35EFFE	4.7	23.6	24.8	45.4	1.5
	S36EFFE	2.5	21.6	39.2	35.5	1.2
	S37EFFE	2.2	14.4	38.5	42.4	2.5
	S38EFFE	6.0	30.3	23.1	39.5	1.2
Participation	S41PART	0.7	7.7	**42.9**	42.7	6.0
	S42PART	6.2	55.3	14.1	23.8	0.5
	S43PART	4.0	27.0	30.3	38.5	0.2
	S44PART	5.0	31.0	36.0	27.3	0.7
	S45PART	5.5	20.6	44.7	28.3	1.0
Transparency	S47TRANS	1.0	13.4	17.6	**65.0**	**3.0**
	S48TRANS	4.5	25.1	20.3	49.1	1.0
	S49TRANS	3.0	44.9	14.6	36.2	1.2
	S50TRANS	3.5	15.6	38.7	37.5	4.7
Accountability	S51ACCO	1.5	7.2	41.4	47.9	2.0
	S52ACCO	1.2	12.9	45.9	39.2	0.7
	S53ACCO	2.5	10.9	**51.6**	34.5	0.5
	S54ACCO	6.7	52.1	34.7	6.0	0.5
	S55ACCO	3.0	17.1	47.9	31.8	0.2
	S56ACCO	3.5	16.1	49.4	29.8	1.2
Capacity	S57CAPA	2.5	14.1	31.3	51.1	1.0
	S58CAPA	0.0	3.5	11.9	**68.2**	**16.4**
	S59CAPA	3.0	37.0	18.1	40.2	1.7
	S60CAPA	0.0	4.7	16.4	**70.7**	8.2
	S61CAPA	0.5	3.2	6.2	**53.3**	**36.7**

Governance dimension	Statements	Completely disagree	Not agree	Undecided/ Neutral	Agree	Completely agree
Conscience	S62CONS	0.0	0.7	1.5	**59.1**	**38.7**
	S63CONS	0.0	0.7	5.7	**45.9**	**47.6**
	S64CONS	0.0	0.0	0.7	**47.6**	**51.6**
	S65CONS	0.7	6.9	5.7	**59.1**	**27.5**
	S66CONS	**56.6**	40.7	1.2	0.7	0.7
	S67CONS	**56.8**	41.2	1.2	0.2	0.5
	S68CONS	3.2	8.7	9.9	**68.0**	**10.2**
	S69CONS	0.2	0.0	1.0	**61.5**	**37.2**
	S70CONS	12.9	51.1	10.2	22.8	3.0
	S71CONS	14.1	64.0	12.9	8.7	0.2
	S73CONS	0.0	0.2	0.7	**60.0**	**39.0**
	S74CONS	4.0	37.7	13.2	39.7	5.5
	S75CONS	9.4	46.7	13.2	29.3	1.5
	S76CONS	0.0	1.5	4.7	**77.4**	**16.4**
	S77CONS	0.0	0.2	1.5	**59.8**	**38.5**
	S78CONS	0.2	5.7	16.4	**65.0**	**12.7**
	S79CONS	0.0	1.0	13.2	**68.0**	**17.9**
	S80CONS	0.5	11.2	11.4	**58.3**	**18.6**

In bold and highlighted values with high percentage of agreement, disagreement, or neutrality among respondents; S11gLOC: formal commitment to sustainability and environmental, social, and economic objectives in the municipality; S12gLOC: the best practices are promoted for tourists and other users who visit the reserve; S13gLOC: the social impacts of the implementation of actions in the PBNR are positive for your municipality; S14gLOC: economic development projects are benefiting indigenous peoples in your municipality; S15gLOC: there exist a formal commitment to the sustainability and social, environmental and economic objectives for your municipality and the PBNR; S16gLOC: economic impacts of the projects implemented in the PBNR are positive; S17gLOC: environmental impacts of the projects implemented by the CMC are positives; S27EFFI: the CMC invests money in updating innovative technological tools to keep the population informed; S28EFFI: residents know the important aspects of the PBNR very quickly – the CMC inform you promptly about the important changes in management in your municipality; S29EFFI: implementation deadlines (of projects) are respected; 3EFFE: residents have access to information immediately; S34EFFE: there exist mechanisms of coordination between CMC and the rest of organizations in the municipality; S35EFFE: (my) municipality is well represented on the Committees that make decisions regarding forest conservation; S36EFFE: projects meet the objectives of the management plan for which they were designed; S37EFFE: CMC manage effectively its relationship with other actors; S38EFFE: CMC has high credibility in the territory; S41PART: representatives of your municipality have easy access to the CMC; S42PART: your representative informs you of the decisions made in the CMC; S43PART: I believe that the CMC is willing to consider recommendations from the civil society in general; S44PART: (My) demands - opinions are channeled by the representative of the municipality to the CMC; S45PART: The CMC handles conflicts appropriately; S47TRANS: I believe that I can access information on forestry projects and good environmental practices if required; S48TRANS: residents can give feedback to the representative of your municipality before the CMC without any problem; S49TRANS: If residents require information on activities related to forest management, they go to the CMC; S50TRANS: There is a flow of information between the municipalities that participate in the CMC; S51ACCO: all the decisions made by the CMC are documented in records; S52ACCO: each member of the CMC have clarity in its role in the committee; S53ACCO: CMC has a clear mandate and vision and there is no duplicity with any other institution/organization in the reserve; S54ACCO: The remuneration of CMC members who receive salaries is publicly known; S55ACCO: indicators of performance of the CMC are clear; S56ACCO: the external evaluations of the CMC have been robust to know the areas for improvement; S57CAPA: Members making the decisions in the CMC have the competencies, leadership, and required experience; S58CAPA: it is necessary to strengthen the functioning of the CMC (i.e., infrastructure - offices-equipment); S60CAPA: subcommittees are optimal for the CMC to perform properly; S61CAPA: I believe that we need other institutions so that they can help in the management of natural resources; S62CON: do you believe that planting trees on my farm helps to improve productivity; S63CONS: do you believe that trees favor infiltration and recharge of water sources; S64CONS: do you believe that trees help in reducing the problems of climate change; S66CONS: I believe that farmers are the only ones who should plant trees on their farms; S67CONS: I believe that coffee growers are the only ones who should plant trees on their farms; S69CONS: I believe that the trees on farm help to reduce climate change; S70CONS: I have included trees on my farm because my best friends have recommended it to me; S71CONS: I always go to a member of the CMC when I need help in which trees to plant; S73CONS: Do you believe that trees help in reducing the effects of climate change; S74CONS: you consider that the actions promoted by the members of the CMC have influenced my opinion regarding the benefits I receive for planting trees; S75CONS: I normally implement on my farm the technical recommendations that CMC members give me; S76CONS: I believe that planting trees on the farm is an investment to earn income in the future; S77CONS: I believe that planting trees on farm helps in reducing the effects of climate change; S78CONS: Do you consider that the natural regeneration areas are an investment to obtain income in the future; S79CONS: Do you believe that natural regeneration areas help water infiltration; S80CONS: I believe that trees provide economic benefits, but I have to wait a long time to reap the benefits.

Christian M., Obi A., Zantsi S., Mdoda L., Jiba P., 2024. The Role of Cooperatives in Improving Smallholder Participation in Agri-Food Value Chains: A Case Study of One Local Municipality in Eastern Cape, South Africa. Sustainability, 16: 2241. https://www.mdpi.com/2071-1050/16/6/2241

CIFOR-ICRAF, nd. So you want to host a multi-stakeholder platform? Designing meaningful, inclusive spaces for transformative change. CIFOR-ICRAF, 4 p. https://www.cifor-icraf.org/knowledge/publication/8891/

Cosgrove D. E., 2003. Landscape and the European Sense of Sight - Eyeing Nature. In: Anderson K., Domosh M., Pile S., Thrift N. (Eds.), Handbook of Cultural Geography. SAGE Publications, London, 249-268. http://dx.doi.org/10.4135/9781848608252.n17

Council of Europe, 2000. Council of Europe Landscape Convention. In: Europe, C.o. (Ed.), ETS No. 176. Council of Europe, Florence. https://www.coe.int/en/web/landscape

Emery M., Flora C., 2006. Spiraling-Up: Mapping Community Transformation with Community Capitals Framework. Journal of the Community Development Society, 37: 19-35. https://doi.org/10.1080/15575330609490152

Escobedo A., 2010. Cadena productiva de cacao de Nicaragua. Documento de Proyecto. Proyecto Cacao Centroamérica. CATIE, Turrialba, Costa Rica, 27 p. https://cadenacacaoca.info/CDOC-Deployment/documentos/Cadena_Productiva_Nicaragua.pdf

GFI, 2009. The governance of forests toolkit (version 1): a draft framework of indicators for assessing governance of the forest sector. The Governance of Forests Initiative. Imazon/ICV/WRI, 69 p. http://pdf.wri.org/working_papers/gfi_tenure_indicators_sep09.pdf

Gutiérrez J. D., 2014. Smallholders' agricultural cooperatives in Colombia: ¿Vehicles for rural development? Revista Desarrollo y Sociedad, 219-271. http://dx.doi.org/10.13043/DYS.73.7

International Cooperative Alliance, 1995. Statement on the Cooperative Identity. ICA News. https://globalyouth.coop/en/cooperative-identity

Jones M., 1991. The elusive reality of landscape. Concepts and approaches in landscape research. Norsk Geografisk Tidsskrift - Norwegian Journal of Geography, 45: 229-244. https://doi.org/10.1080/00291959108552277

Larson A. M., Sarmiento Barletti J. P., 2020. Diseño para la participación: Aprendizajes para foros multiactor más equitativos y resilientes, CIFOR, 8 p. https://doi.org/10.17528/cifor/007836

León Leiva K., 2014. Identidad territorial como contribución a los procesos de gobernanza territorial. Un análisis del contexto socio institucional en la zona del Macizo Peñas Blancas, Nicaragua. Maestría en Práctica del Desarrollo. CATIE, Turrialba, Costa Rica, 120 p. https://repositorio.catie.ac.cr/handle/11554/7163

Lockwood M., Davidson J., Curtis A., Stratford E., Griffith R., 2010. Governance principles for natural resource management. Society & Natural Resources, 23: 986-1001. https://doi.org/10.1080/08941920802178214

Majee W., Hoyt A., 2011. Cooperatives and Community Development: A Perspective on the Use of Cooperatives in Development. Journal of Community Practice, 19: 48-61. https://www.tandfonline.com/doi/full/10.1080/10705422.2011.550260

Mendoza Rivarola C. A., 2015. Definición de principios y criterios para la orientación de procesos de Territorios Climáticamente Inteligentes (TCI). CATIE, Turrialba, Costa Rica, 97 p. https://repositorio.catie.ac.cr/handle/11554/7218?locale-attribute=es

Mercado L., Villarreyna R., Cerda R., Danilo P., Aguilar A., Echeverría J., et al., 2017. Promoviendo prácticas Agrícolas Climáticamente Inteligentes para enfrentar los efectos del cambio y la variabilidad climática en Trifinio. Policy Brief. Sintesis para decisores. CATIE, Turrialba, Costa Rica, 6 p. https://repositorio.catie.ac.cr/handle/11554/8651

Ministerio del Ambiente y los Recursos Naturales, 2021. Actualización Plan General de Manejo del área protegida Reserva Natural Macizo de Peñas Blancas. Resolución Ministerial N°. 271-2021. La Gaceta, Nicaragua. http://legislacion.asamblea.gob.ni/normaweb.nsf/3133c0d121ea3897062568a1005e0f89/5aedec5e8b750fc6062587ae0072a75a?OpenDocument

Montoya J., Junkin R., Gottret V., Stoian D., 2013. Posicionamiento y gobernanza de Cacaonica en la cadena de valor del cacao orgánico de Nicaragua. Agroforestería en las Américas, 43: 78-84. https://repositorio.catie.ac.cr/handle/11554/6680

Montoya Zumaeta J., 2009. Posicionamiento y gobernanza de organizaciones de productores en cadenas de valor globales: el caso de la cooperativa nicaragüense CACAONICA. Escuela de Posgrado, CATIE, Turrialba, Costa Rica, 141 p. https://www.researchgate.net/publication/315722630_Posicionamiento_y_gobernanza_de_Cacaonica_en_la_cadena_de_valor_del_cacao_organico_de_Nicaragua

Münter A., Osterhage F., 2018. Concepts of spatial planning (Raumordnung). Academy for territorial development in the Leibniz Association, Hannover, 53 p. https://www.arl-international.com/sites/default/files/dictionary/2021-08/concepts_of_spatial_planning.pdf

Olwig K. R., 1996. Recovering the Substantive Nature of Landscape. Annals of the Association of American Geographers, 86: 630-653. https://avblivinglandscape.wordpress.com/wp-content/uploads/2011/01/olwig_1996.pdf

Pinto-Correia T., Kristensen L., 2013. Linking research to practice: The landscape as the basis for integrating social and ecological perspectives of the rural. Landscape and Urban Planning, 120: 248-256. https://doi.org/10.1016/j.landurbplan.2013.07.005

Primdahl J., Søderkvist Kristensen L., Arler F., Angelstam P., Aagaard Christensen A., Elbakidze M., 2018. Rural landscape governance and expertise: on landscape agents and democracy. In: Egoz S., Jørgensen K., Ruggeri D. (Eds.), Defining Landscape Democracy: A Path to Spatial Justice. Edward Elgar Publishing. Social and Political Science, Cheltenham, 153-164. https://doi.org/10.4337/9781786438348.00024

R Core Team, 2015. R: A language and environment for statistical computing. In: Computing, R.F.f.S. (Ed.). R Foundation for Statistical Computing, Vienna, Austria, 1596 p. https://ringo.ams.stonybrook.edu/images/2/2b/Refman.pdf

Rana P., Chhatre A., 2017. Beyond committees: Hybrid forest governance for equity and sustainability. Forest Policy and Economics 78, 40-50. https://doi.org/10.1016/j.forpol.2017.01.007

Reed J., Barlow J., Carmenta R., van Vianen J., Sunderland T., 2020a. Engaging multiple stakeholders to reconcile climate, conservation and development objectives in tropical landscapes. In: Reed J., Ros-Tonen M., Sunderland T. (Eds.), Operationalizing integrated landscape approaches in the tropics. CIFOR, Bogor, Indonesia, 17 p. https://www.cifor-icraf.org/publications/pdf_files/Books/2020-COLANDS-04.pdf

Reed J., Ickowitz A., Chervier C., Djoudi H., Moombe K., Ros-Tonen M., et al., 2020b. Integrated landscape approaches in the tropics: A brief stock-take. Land Use Policy 99, 99: 104822. https://doi.org/10.1016/j.landusepol.2020.104822

Reed J., Van Vianen J., Deakin E. L., Barlow J., Sunderland T., 2016. Integrated landscape approaches to managing social and environmental issues in the tropics: learning from the past to guide the future. Global Change Biology, 22: 2540-2554. https://doi.org/10.1111/gcb.13284

Robinson G. M., 2019. Landscape science for natural resource management in a Globalised World. In: Mueller L., Eulenstein F. (Eds.), Current Trends in Landscape Research. Springer, Cham, Switzerland, 83-104. https://doi.org/10.1007/978-3-030-30069-2_4

Robinson G. M., Carson D. A., 2013. Applying Landscape Science to Natural Resource Management. Ecology and Society, 18 (1): 32. http://dx.doi.org/10.5751/ES-05639-180132

Rodríguez Cortes Á. M., Ospina Rojas D. F., 2016. Construcción participativa de estrategias de desarrollo sostenible bajo cambio climático en el territorio Macizo de Peñas Blancas, Nicaragua. Maestrias en práctica del desarrollo y en práctica de la conservación de la biodiversidad. CATIE, Turrialba, Costa Rica, 177 p. https://repositorio.catie.ac.cr/handle/11554/8564

Ros-Tonen M., Derkyi M., Insaidoo T., 2014. From Co-Management to Landscape Governance: Whither Ghana's Modified Taungya System? Forests, 5: 2996-3021. https://doi.org/10.3390/f5122996

Ros-Tonen M., Insaidoo T. F. G., Acheampong E., 2013. Promising start, bleak outlook: The role of Ghana's modified taungya system as a social safeguard in timber legality processes. Forest Policy and Economics, 32: 57-67. https://doi.org/10.1016/j.forpol.2012.11.011

Roudometof V., 2021. What is glocalization? Réseaux, 226-227, 25 p. https://shs.cairn.info/journal-reseaux-2021-2-page-45?lang=en

Ruano-Chamorro C., Gurney G. G., Cinner J. E., 2021. Advancing procedural justice in conservation. Conservation Letters, 15: 12861. https://doi.org/10.1111/conl.12861

Sarmiento Barletti J. P., Larson A. M., Hewlett C., Delgado D., 2020. Designing for engagement: A Realist Synthesis Review of how context affects the outcomes of multi-stakeholder forums on land use and/or land-use change. World Development, 127: 104753. https://doi.org/10.1016/j.worlddev.2019.104753

Sayer J., Sunderland T., Ghazoul J., Pfund J. L., Sheil D., Meijaard E., et al., 2013. Ten principles for a landscape approach to reconciling agriculture, conservation, and other competing land uses. USA, Procedure National Academy of Science, 110: 8349-8356. https://doi.org/10.1073/pnas.1210595110

Scherr S. J., Shames S., Friedman R., 2012. From climate-smart agriculture to climate-smart landscapes. Agriculture & Food Security, 1: 12. https://doi.org/10.1186/2048-7010-1-12

Secco L., Da Re R., Pettenella D. M., Gatto P., 2014. Why and how to measure forest governance at local level: A set of indicators. Forest Policy and Economics, 49: 57-71. https://doi.org/10.1016/j.forpol.2013.07.006

Sepúlveda N., Vågen T.-G., Winowiecki L., Ordoñez J., Chiputwa B., Makui P., et al., 2020. Sentinel Landscape stocktaking pilot study: Report Nicaragua-Honduras. Working Paper 2. The CGIAR Research Program on Forests, Trees and Agroforestry (FTA), Bogor, Indonesia. https://doi.org/10.17528/cifor/007537

Silva R.F.B.D., Batistella M., Moran E. F., 2017. Socioeconomic changes and environmental policies as dimensions of regional land transitions in the Atlantic Forest, Brazil. Environmental Science & Policy, 74: 14-22. https://doi.org/10.1016/j.envsci.2017.04.019

Swagemakers P., Domínguez García M. D., Milone P., Ventura F., Wiskerke J. S. C., 2019. Exploring cooperative place-based approaches to restorative agriculture. Journal of Rural Studies, 68: 191-199. https://doi.org/10.1016/j.jrurstud.2018.12.003

Swyngedouw E., 1997. Neither global nor local: "glocalization" and the politics of scale. In: Cox K. (Ed.), Spaces of Globalization: Reasserting the Power of the Local. Guilford Press, New York, 137-166.

Tucker C. M., 2010. Learning on governance in forest ecosystems: Lessons from recent research. International Journal of the Commons, 4: 687-706. https://thecommonsjournal.org/articles/10.18352/ijc.224

Ubandoma G. A. N. I., Umar A., Abubakar B. Z., Yusuf A. T., Malabe K. M., Adamu A. S., 2022. Role of Rural Cooperatives on Agricultural Development in Zaria Local Government Area of Kaduna State, Nigeria. Journal of Agriculture and Environment, 17: 25-36. https://www.ajol.info/index.php/jagrenv/article/view/235380

UN Economic and Social Commission for Asia and the Pacific, 2003. What is Good Governance? UNESCAP, Bangkok, Thailand, 3 p. https://www.unescap.org/sites/default/files/good-governance.pdf

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Characterisation and statistical modelling of shear strength in 12 hardwood timber species from the Congo Basin

Photo 1.
Example of outdoor application of three of the characterised species, Azobé, Okan and Tali: https://www.houtindegww.nl/project/het-wrakhout-wenduine/
"Het Wrakhout" bridge combined with a cycle path and pedestrian walkway - Welduine, Belgium.
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RÉSUMÉ

Caractérisation de la résistance au cisaillement du bois de 12 essences feuillues du Bassin du Congo et modélisation statistique

La résistance au cisaillement est une propriété du bois fondamentale pour la conception de produits et de constructions à base de bois. Les connaissances actuelles sont insuffisantes pour prédire cette propriété, principalement en raison du grand nombre d'essences présentes dans le Bassin du Congo. L'objectif principal de cette étude était de proposer une qualification préliminaire du cisaillement pour les essences du Bassin du Congo, en prenant en compte sa variabilité. Pour ce faire, nous avons étudié 12 essences aux propriétés très différentes, de la moins dense à la plus dense. La résistance des bois au cisaillement a été déterminée expérimentalement selon les spécifications des normes européennes, à l'échelle du matériau bois utilisé. Une analyse statistique a été réalisée. Pour réduire la variabilité de la résistance au cisaillement, les essences ont été réparties en quatre groupes distincts selon les spécifications de l'Institut FCBA. En vue de proposer des contraintes admissibles qui faciliteraient la prise de décision, la qualité relative de l'ajustement de cinq modèles probabilistes de distribution de la résistance au cisaillement a été évaluée (normale, log-normale, exponentielle, Weibull à 2 paramètres et Weibull à 3 paramètres). Les résultats de la régression géométrique (R^2 = 0,81) montrent que la résistance au cisaillement est fortement corrélée à la densité. Elle peut être prévue de manière plus fiable avec la distribution de Weibull à trois paramètres qu'avec les autres distributions. Les résultats de cette étude ouvrent de nouvelles perspectives au regard de la résistance au cisaillement, qui sont à prendre en compte pour la conception de produits bois à partir d'essences tropicales du Bassin du Congo.

Mots-clés : ANOVA, valeur caractéristique, essences feuillues tropicales, qualité des bois de feuillus, conception fiable, distribution statistique, Bassin du Congo.

ABSTRACT

Characterisation and statistical modelling of shear strength in 12 hardwood timber species from the Congo Basin

Shear strength is a wood property that is fundamental to the design of wood-based products and constructions. This property cannot currently be predicted due to insufficient knowledge, primarily because of the large number of timber species found in the Congo Basin. The main aim of this study was to provide a preliminary qualification of shearing in Congo Basin timber species, with consideration for its variability. For this purpose, we studied 12 timber species with very different properties, from the least dense to the densest. Their shear strength was determined experimentally using European standard specifications, on the scale of the wood material used. A statistical analysis was conducted. To reduce shear strength variability, the species were assigned to four distinct clusters defined according to FCBA Institute specifications. With a view to developing allowable design stresses to facilitate decision-making, we evaluated the relative goodness-of-fit of five probabilistic shear strength distributions (normal, lognormal, exponential, Weibull 2 parameters and Weibull 3 parameters) that are used in wood-related applications. The results of geometric regression (R^2 = 0.81) show that shear strength is well correlated with density. Shear strength can be more reliably predicted with the three-parameter Weibull distribution than with the other distributions. The findings of this study open up new prospects to be considered for the design of wood-based products with regard to shear, when using tropical timber species from the Congo Basin.

Keywords: ANOVA, characteristic value, tropical hardwood species, hardwood quality, reliable design, statistical distribution, Congo Basin.

RESUMEN

Caracterización y modelado estadístico de la resistencia a la cizalla en 12 especies de madera dura de la cuenca del Congo

La resistencia a la cizalla es una propiedad de la madera fundamental para el diseño de productos basados en la madera y en la construcción. Esta propiedad no se puede predecir actualmente a causa de la falta de conocimientos suficientes, principalmente por el gran número de especies madereras que se encuentran en la cuenca del Congo. El principal objeto de este estudio es proporcionar una cualificación preliminar de la resistencia a la cizalla en las especies madereras de la cuenca del Congo, considerando su variabilidad. Con este objetivo, estudiamos 12 especies madereras con propiedades muy diferentes, desde la menos densa a la más densa. Su resistencia a la cizalla se determinó experimentalmente mediante las especificaciones de las normas europeas, en la escala del material maderero utilizado. Se llevo a cabo un análisis estadístico. Para reducir la variabilidad de la resistencia a la cizalla, las especies se asignaron a cuatro grupos diferentes definidos según las especificaciones del Instituto FCBA. Con el objeto de desarrollar diseños con limitaciones permisibles que faciliten la toma de decisiones, evaluamos la relativa adecuación de cinco distribuciones probabilísticas de resistencia a la cizalla (normal, logonormal, exponencial, Weibull de 2 parámetros y Weibull de 3 parámetros) que se utilizan en aplicaciones madereras. Los resultados de la regresión geométrica (R^2 = 0.81) muestran que la resistencia a la cizalla tiene una buena correlación con la densidad. La resistencia a la cizalla puede predecirse de manera más fiable con la distribución de Weibull de tres parámetros que con las otras distribuciones. Los descubrimientos de este estudio abren nuevas posibilidades en el diseño de productos madereros respecto a la resistencia a la cizalla, utilizando especies de madera tropical de la cuenca del Congo.

Palabras clave: ANOVA, valor característico, especies de madera dura tropical, calidad de la madera dura, diseño fiable, distribución estadística, cuenca del Congo.

Introduction

The shear strength is a fundamental property of wood, generally used in timber structure design and modelling (Guitard 1987; Khokhar et al. 2010). It refers to the ability to resist internal slipping of one part upon another (Green et al. 1999). It can be considered such as the stress required to yield or fracture the material in the plane of material cross-section (Cubberly 1993). This makes it possible to identify the failure criteria of wood-based products subjected to combined stresses, such as tension-shear (Lavalette et al. 2012). Concerning engineered wood products such as glulam, the quality of the integrity between laminations can be assessed by using the wood shear strength (Aicher et al. 2018). The shear properties also drive the behaviour of timber structures under torque (Ayina and Morlier 1998). They are essential to calculate timber connections (Rodrigues et al. 2023). They can be needed while analysing the stability of columns and girders (Brandner and Schickhofer 2015). Despite the importance of these various arguments, there is a lack of knowledge concerning the shear strength of tropical hardwood species from the Congo Basin, which currently results in under- or over-dimensioning structural elements (Cunha et al. 2021). Indeed, these species are mainly appreciated for their interesting appearance and favourable physical and mechanical properties for structural use (Cunha et al. 2021; Lanvin et al. 2009). However, several databases describing the technological properties of central African species, such as Tropix 7.5.1 (Paradis et al. 2015) and ITTO (ITTO 2001), do not provide information concerning the shear properties. This can be explained by three main factors. The first one is the high diversity of central African timber species. More than 300 timber species present potential to be used for structural purposes, and about sixty of them are regularly exploited each year (Vivien and Faure 1995; Eba'a Atyi et al. 2013). Therefore, performing shear tests for all tropical timber species available in the Congo Basin would be time-consuming and expensive. The second factor is the lack of research initiatives aiming at the promotion of lesser-known species from the Congo Basin (Ayina 2002). Thirdly, standards concerning the use of hardwood products for structural purposes are missing in central African countries (Bourreau et al. 2013).

Due to the high number of exploited timber species in Central African forests, investigations concerning a fundamental property such as the shear strength need to be oriented towards the production of technical and simplified information for timber structure designers, industrial wood producers, and consumers. In that perspective, clustering specifications were elaborated by the FCBA Institute (2015). They enable the categorisation of hardwood species into groups, from lower to superior, based on their density range at 12% moisture content: "very light" (230-500 kg/m³), "light" (500-650 kg/m³), "medium heavy" (650-865 kg/m³), and "heavy" (865-1,000 kg/m³). These specifications are compatible with various classifications of hardwood timber species, formalised by authors such as Sallenave (1955) and Wong (2002). They are essential for meaningful and cost-optimal use of wood since the technological properties of most of the species are poorly known (Chowdhury et al. 2014). They also support the idea that, in each cluster, timber species may be interchangeably used for similar structural applications, since the wood density is one of the most critical parameters influencing the technological performance of timber products (Zziwa et al. 2006). They have the potential to be used as a tool for preserving highly exploited species and promoting the use of lesser-known species. They may be used easily for design purposes since the density is one of the most important parameters correlated with the technological features of timber species (natural durability, processing difficulty, mechanical strength, modulus of elasticity, gluing ability). The previous arguments support the idea that the FCBA Institute specifications are useful for: (i) designing hardwood timber structures since the density allows to define clearly the areas in which timber species may be used; (ii) analysing and simplifying the shear features of timber species from the Congo Basin. However, it is difficult to find reliable information on shear strength properties attached to these specifications. Using these specifications for investigating the distribution of the shear strength would draw a preliminary picture of that property, which is a main prerequisite needed while designing structures with timber species from the Congo Basin. This can be done by analysing the probabilistic models of the shear strength.

The use of probability functions to model the strength distribution of solid wood is of interest for two major reasons: the representation of the variability of the strength property and the reliability-based design procedures. Concerning the first point, it is well known that wood properties are highly variable within and between trees due to the complexity of wood formation (Pyorala et al. 2019). Such variability may be amplified in the presence of several timber species in a given specification cluster, even if their average densities are fairly similar. As a consequence, a timber strength property can be considered as a random variable. Not considering the variability while analysing a strength property may generate some unfavourable effects of any isolated element (in a construction project), in which constraints of security are extremely important and lead to structural inefficiency. Probabilistic models are therefore needed for specifying the variability (distribution) of the shear strength in each cluster. Moreover, it would be useful to analyse how the specification groups may influence the nature of the probabilistic model. The choice of probability distribution is generally guided by goodness-of-fit analysis. This analysis has been mainly made for strength properties in bending of timber (Modulus of Rupture, MOR) (Castera and Morlier 1994). However, scientific literature lacks information concerning the probabilistic modelling of the shear strength of timber species from the Congo Basin.

Concerning the second point, the probability distribution models of the shear strength are useful for (Foschi 2005): (i) calibrating the main parameters needed in a codified design (the 5% characteristic values, for instance); (ii) customising the design of a structure to meet specified performance with associated target reliability level. They enable more accurate safety analysis for hardwood timber structures (Czmoch 2021).

Several studies concerning the shear strength of tropical hardwood species were carried out and reported in the literature. Hernandez and Almeida (2003) investigated the effects of wood density and interlocked grain on the shear strength parallel to grain, based on three Peruvian timber species, namely Ishpingo (*Amburana cearensis* A.C. Smith), Pumaquiro (*Aspidosperma macrocarpon* Mart.), and Tulpay (*Clarisia racemosa* Ruiz & Pav.). They found that the interlocked grain negatively affected actual shear strength. Alves et al. (2013) used a non-destructive approach, namely the drill resistance, to estimate the shear strength of seven Brazilian tropical woods with densities varying from 650 to 1,150 kg/m^3. The results were validated thanks to good correlations (R^2 varying from 0.59 to 0.75) with shear tests performed in the longitudinal, tangential, and radial directions according to the Brazilian Standard NBR 7190 (1997). Ravenshorst et al. (2016) observed that the current shear strength values for high-density tropical hardwoods were very low compared to the values for softwoods, according to European strength class tables. As a solution approach, they investigated massaranduba wood, originating from Brazil, according to EN 408+A1 (2012). They found that the 5% value for the shear strength value of massaranduba was twice as high as the standardised value for strength class D70. Rodrigues et al. (2023) conducted similar investigations on Brazilian woods, considering the influence of growth rings position of wood. Wolensky et al. (2020) evaluated the accuracy of the relation proposed by NBR 7190 (1997) of shear strength along the grain to compression strength along the grain, based on 40 Brazilian wood species. The statistical analysis revealed that the geometric regression was the model of best fit. Yusoh et al. (2022) evaluated the effect of heat treatment on surface roughness, shear strength, and hardness of two tropical wood species from Malaysia, namely Batai (*Paraserianthes falcataria*) and Sesendok (*Endospermum malaccense*). In contrast to the untreated wood species, the heat-treated wood species exhibited lower values of shear strength. The shear of both species was adversely influenced by heat exposure. Ndong-Bidzo et al. (2021) performed shear compressive tests on various glue joints to understand the failure mode of glue-laminated timber made up of mixed tropical wood species during a 3-point bending behaviour. The shear specimens used were mortar-type masonry with two glue joints tested, according to EN 1052-3 (2003) specifications. These investigations have the potential to provide interesting information on the shear failure mode of two glue joints simultaneously. However, they need to be adapted and conducted on tropical solid woods from the Congo Basin.

As a major observation based on the literature review, it is difficult to find consistent information concerning the shear modelling of hardwood timbers from the Congo Basin. A traditional qualification process would be expensive and time-consuming since the number of timber species may be important. Moreover, the variability of that strength property was not considered in the available studies. The main objective of this study is to specify a preliminary qualification of Congo Basin timber species with regard to shear, in which the variability is considered. The research question is how the FCBA clustering specifications (FCBA Institute 2015) may be used to provide simple and useful information needed to facilitate the decision-making process while designing structures vis-à-vis the shear strength. Twelve (12) timber species with very different properties will be considered and assigned in the FCBA technological clusters. We assume that these clusters are homogeneous. That hypothesis will be justified in the data analysis section.

Table I.
Properties of 12 selected timber species of the Congo Basin at 12% moisture content (Paradis et al. 2015)

Selected timber species	Average density (kg/m^3)	Average flexural modulus of rupture (MOR) (MPa)	Average longitudinal modulus of elasticity (MOE) (MPa)
Abura (*Mitragyna ciliata*)	600	78	11.020
Ayous (*Triplochiton scleroxylon*)	430	52	7.260
Azobé (*Lophira alata*)	1,060	162	21.420
Bilinga (*Nauclea diderrichii*)	760	95	14.660
Dabema (*Piptadeniastrum africanum*)	700	98	15.190
Difou (*Morus mesozygia*)	840	143	18.490
Doussie (*Afzelia africana*)	800	124	17.020
Frake (*Terminalia superba*)	540	80	11.750
Movingui (*Distemonanthus benthamianus*)	730	116	14.740
Okan (*Cylicodiscus gabunensis*)	910	134	22.260
Padouk (*Pterocarpus soyauxii*)	790	116	15.870
Tali (*Erythrophleum ivorense*)	910	128	19.490

Material and Methods

Selection of timber species

The twelve species selected in this study are Abura (*Mitragyna ciliata*), Ayous (*Triplochiton scleroxylon*), Azobe (*Lophira alata*), Bilinga (*Nauclea diderrichii*), Dabema (*Piptadeniastrum africanum*), Difou (*Morus mesozygia*), Doussie (*Afzelia africana*), Frake (*Terminalia superba*), Movingui (*Distemonanthus benthamianus*), Okan (*Cylcodiscus gabunensis*), Padouk (*Pterocarpus soyauxii*), and Tali (*Erythrophleum ivorense*). Their strength properties at 12% Moisture Content (MC) are presented in table I (Paradis et al. 2015). Their longitudinal modulus of elasticity (MOE) values varied from 7,260 MPa to 22,060 MPa, and the flexural modulus of rupture (MOR) from 52 MPa to 162 MPa (Paradis et al. 2015). They present a wide range of use in several structural applications, such as panels, bridges, and flooring (Paradis et al. 2015).

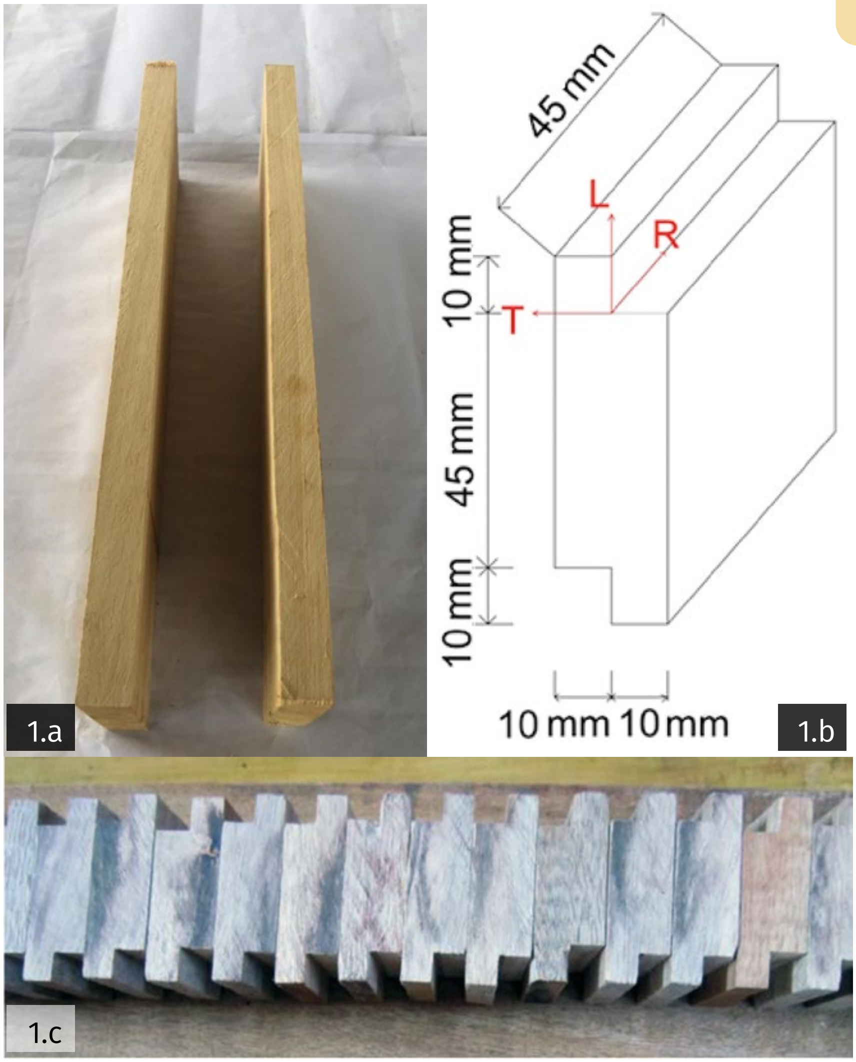

Figure 1.
Features of the shear specimens: 1.a A view of Tali (*Erythrophleum ivorense*) and Frake (*Terminalia superba*) wood lamellae;
1.b Dimensions and orthotropic directions of the specimens;
1.c Shear specimens manufactured using Abura (*Mitragyna ciliata*) species.

Preparation of shear test specimens

For each species, five quarter-sawn boards (length: 220 cm; width: 40 cm; thickness: 30 cm) were bought in different timber markets in the city of Yaoundé (Cameroon). They were composed of heartwood without defects and knots, and supplied with high MC. The quarter-sawn orientation of wood is useful to minimise the dimensional shrinkage during drying. General information about the trees of each species may be found in databases such as Prota4U[1]. Each board was planned and sawn into “lamellae” of 400 mm long and 150 mm wide. The thickness of the lamellae was around 26 mm. This operation allowed the wood to dry out for the first time. For each species, a batch of 10 lamellae (2 lamellae for a board) was stored in a climate chamber (temperature 20% ± 2% °C and relative humidity 65% ± 5%) for three months. Under these conditions, the MC of the wood at hygroscopic equilibrium stabilised at around 12%. Before manufacturing the test specimens, the wood was planned and the final average thickness was around 20 mm. For each board, two shear specimens were manufactured. The features of the specimen are illustrated in figure 1. The shape of the specimens was designed to enable a self-aligning seat, ensuring uniform lateral distribution of the load. Before carrying out the shear test, the dimensions and mass of each specimen were measured. This enabled us to deduce their density. At the end of the tests, each broken specimen was stored in an oven at 105 °C, until the corresponding mass stabilised. That step enabled us to determine the moisture content of the specimens corresponding to their ultimate shear strength.

Shear test

A shear stress parallel to grain was applied (figure 2), using a compressive load, in the solid wood (specimen) at a constant speed of 0.6 mm/min until failure occurs. The testing procedures were very close to those described in the EN 392 (1995) standard. They are similar to those specified by the NBR 7190 standard (1997) and the Nord American ASTM standard (D143). The NBR 7190 standard was successfully used by Wolensky et al. (2020) to assess the shear strength of Brazilian hardwood timbers. The ultimate shear strength f_v was calculated according to equation 1:

[1] www.prota4u.org

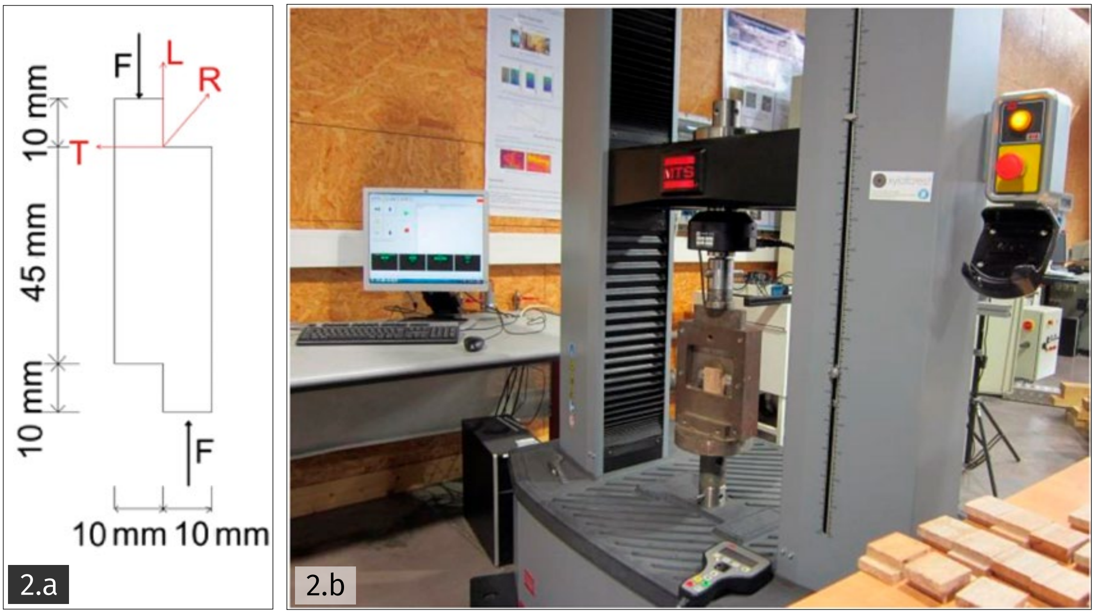

Figure 2.
Principle of the shear compressive test and sample device. 2.a Sample used for the shear compressive test and related loading condition; 2.b Shear compressive test device.
Photos O. Niapi.

$$f_v = k_v \frac{F_u}{A} \text{ (in N/mm}^2\text{)} \quad \text{(equation 1)}$$

where F_u is the ultimate load (in N), A is the sheared area (in mm^2), K_v is the correction scale factor (equation 2):

$$K_v = 0.78 + 0.0044t \quad \text{(equation 2)}$$

where t is the thickness (in mm). Figure 2 illustrates the shear test device and the loading conditions.

Assignment of timber species into FCBA clusters

The average density of each timber species was estimated, making it possible to assign each species to a specific FCBA timber cluster (FCBA Institute 2015). We recall that the specifications enabled an organisation of the hardwood timber species into several clusters, among which: “very light” (230-500 kg/m^3), “light” (500-650 kg/m^3), “medium heavy” (650-865 kg/m^3), and “heavy” (865-1,000 kg/m^3). Hardwood timber species clustering is an appropriate tool to simplify the production of technical information such as shear strength and facilitate a decision-making process while designing wood structures.

Analysis of variance

A one-factor analysis of variance (ANOVA) test at a 5% significance level was carried out to assess the overall significant difference between the means of the shear strength within the timber species and the clusters. Two hypotheses were considered: H_0 (the means are equal (null hypothesis)); H_1 (the means are different). By ANOVA formulation, a p-value (p probability) lower than the adopted significance level (0.05) implies that the average values of the shear strength are statistically different, or equivalent otherwise (p-value ≥ 0.05). To identify where the differences between the groups lie, a Tukey HSD (Honestly Significance Difference) test was carried out to determine which means are different, with a significance level of 0.05. The ANOVA and Tukey HSD tests were computed thanks to the MINITAB 16 software.

Identification of the probabilistic distribution of the shear strength

The Goodness of Fit (GOF) test was performed to specify the statistical distribution of the shear strength, thanks to the MINITAB 16 software. There is a wide range of tests available in the literature to determine whether a sample could have been drawn from a specific distribution. Among them, we used the Anderson-Darling (AD) for the following reasons (Romeu 2003): (1) the ability to detect variations in the probability distribution’s overall shape; (2) a good adaptation for both small and large samples; (3) the use of the specific distribution in calculating critical values (CD). This has the advantage of allowing a more sensitive test. Moreover, it is widely used and may be considered as an alternative to the chi-square and Kolmogorov-Smirnov GOF tests. The AD statistic is (equation 3):

$$AD = -n + \sum_{i=1}^{i=n} \frac{1-2i}{n} \left[Ln\left(F\left(Y_i\right)\right) + Ln\left(1 - F\left(Y_{(N+1-i)}\right)\right) \right] \quad \text{(equation 3)}$$

where F is the assumed distribution; Y_i is the ith sorted, standardised sample value; n is the sample size. The null hypothesis, which states that “the data follow a specified distribution,” is then rejected at a significance level of 0.05 if the AD statistic is greater than the critical value CD. The CD value is, in the case of normal distribution, given by equation (4):

$$CD = \frac{0.752}{1 + \frac{0.75}{n} + \frac{2.25}{n^2}} \quad \text{(equation 4)}$$

Five probability distributions were considered: normal, log-normal, 3-parameter Weibull, exponential, and 2-parameter Weibull (equations 5-9). They can be used for modelling the wood properties (de Melo et al. 2000).

- Normal distribution (equation 5):

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(\frac{-(x-\mu)^2}{2\sigma^2}\right) \quad \text{(equation 5)}$$

where μ is the mean and σ the standard deviation.

- Log-normal distribution (equation 6):

$$f(x) = \frac{1}{S\sqrt{2\pi}} \exp\left(\frac{-(Ln(x)-M)^2}{2S^2}\right) \quad \text{(equation 6)}$$

where *M* is the mean of *Ln(x)* and *S* the standard deviation of *Ln(x)*.

- 3-parameter Weibull distribution (equation 7):

$$f(x) = \frac{m}{w}\left(\frac{x-a}{w}\right)^{m-1} \exp\left(-\left(\frac{x-a}{w}\right)^m\right) \quad \text{(equation 7)}$$

where *a* is the location parameter, *m* is the shape parameter, *w* is the scale parameter.

- Exponential distribution (equation 8):

$$f(x) = \lambda \exp(-\lambda x) \, if \, x \geq 0 ; f(x) = 0 \, if \, x < 0 \quad \text{(equation 8)}$$

where λ is the rate parameter.

- 2-parameter Weibull distribution (equation 9):

$$f(x) = \frac{m}{w}\left(\frac{x}{w}\right)^{m-1} \exp\left(-\left(\frac{x}{w}\right)^m\right) \quad \text{(equation 9)}$$

where *m* is shape parameter, *w* is scale parameter.

Results

Shear strength of the timber species

The shear strength of the 12-timber species globally ranged from 5.68 MPa (the minimum value) to 23.88 MPa (the maximum value), with a mean of 13.21 MPa and a standard deviation of 4.30 MPa. Figures 3, 4, and 5, respectively, show the post-test image of some specimens, the plot of the shear strength of the specimens versus wood density at around 12% MC, and the plot of the average shear strength versus average wood density of each specimen. Table II displays experimentally obtained mean values for the selected hardwood species. It shows that the best estimation of the shear strength is obtained by using the geometric regression model (R^2 = 0.74) (figure 4). The linear, logarithmic, polynomial, and exponential models underestimate the R^2 coefficient (table III). Such a trend is confirmed while estimating the mean shear strength value by using the mean density of the timber species (R^2 = 0.81) (figure 5). Results of the one-factor ANOVA test are presented in table IV.

Figure 3.
Post-test image of two specimens of Abura (*Mitragyna ciliata*) wood.

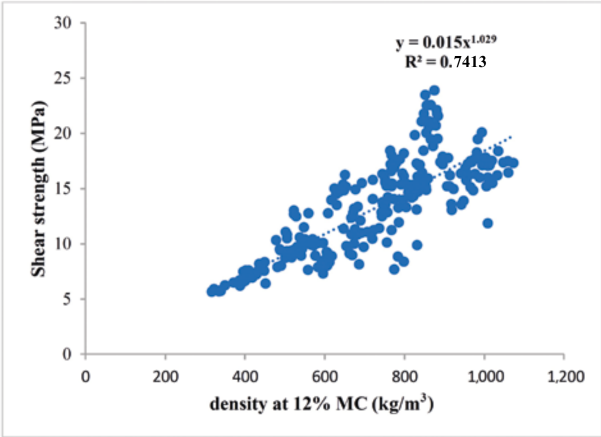

Figure 4.
Plot of the shear strength versus wood density at 12% moisture content of 12 selected timber species of the Congo Basin.

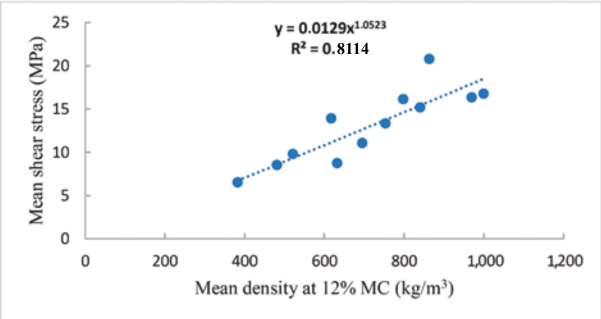

Figure 5.
Plot of the average shear strength versus average wood density at 12% moisture content.

According to the null hypothesis, the means of the shear strength of the timber species are all equal or equivalent. The p-value is less than the significance level of 0.05. We can therefore reject the null hypothesis and conclude that the shear strength of the timber species presents significantly different trends.

Clustering and probabilistic modelling of the shear strength

Results of the assignment procedure showed that the 12-timber species can be organised in four clusters, labelled 1 to 4: cluster 1 (very light hardwoods): Ayous, Frake; cluster 2 (light hardwoods): Abura, Movingui, and Dabema; cluster 3 (medium heavy hardwoods): Difou, Bilinga,

Table II.
Mean strength values at 12% moisture content for 12 selected timber species of the Congo Basin.

Selected timber species	Cluster	Density (kg/m^3)		Experimental values of Shear strength (MPa)		Bibliographical values	
		Mean	Standard deviation	Mean	Standard deviation	Values (MPa)	References
Abura (*Mitragyna ciliata*)	Cluster 2	521	28	9.83	0.89	8-9	Nyunai Nyemb (2011)
Ayous (*Triplochiton scleroxylon*)	Cluster 1	383	37	6.56	0.57	3-8 6.8	Bosu and Krampah (2005) Green et al. (1999)
Azobé (*Lophira alata*)	Cluster 4	1,000	49	16.78	1.02	-	-
Bilinga (*Nauclea diderrichii*)	Cluster 3	841	37	15.18	1.18	8.5 - 17	Oppuni-Frimpong and Oppuni-Frimpong (2012)
Dabema (*Piptadeniastrum africanum*)	Cluster 2	617	55	13.95	1.48	7 - 18	Takofou (2008)
Difou (*Morus mesozygia*)	Cluster 3	798	29	16.13	1.62	-	-
Doussie (*Afzelia africana*)	Cluster 3	753	53	13.33	2.02	7.5 - 14	Gérard and Louppe (2011)
Frake (*Terminalia superba*)	Cluster 1	481	63	8.57	1.21	4.5 - 10 9.7	Sosef et al. (1995) Green et al. (1999)
Movingui (*Distemonanthus benthamianus*)	Cluster 2	632	73	8.77	0.81	12.5 - 14.5	Owusu and Loupe (2012)
Okan (*Cylicodiscus gabunensis*)	Cluster 4	866	17	20.81	1.82	8-22	Ayarkwa and Owusu (2008)
Padouk (*Pterocarpus soyauxii*)	Cluster 3	695	34	11.10	1.45	-	-
Tali (*Erythrophleum ivorense*)	Cluster 4	970	26	16.35	2.04	-	-

Table III.
Regression models for the shear strength estimation.

Regression models	Equation	R^2
Linear	$0.018x + 0.08$	0.66
Geometric	$0.015x^{1.029}$	0.74
Logarithmic	$12.044Ln(x) - 65.435$	0.67
Polynomial	$-10^{-5}x^2 + 0.0378x - 6.1694$	0.68
Exponential	$4.135e^{0.0015x}$	0.71

x: density of the specimen at 12% moisture content.

Table IV.
Results of the ANOVA for the sample sets.

Source	DF	SS	MS	F value	p value
Factor	11	3,892.83	353.89	177.32	0.000
Error	221	441.06	2.00		
Total	**232**	**4,333.89**			

DF: degrees of freedom; SS: sum of squares; MS: mean squares.

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Table V.
Characteristics of the shear clusters.

Clusters	Density (kg/m³)		Shear strength (MPa)		Weibull parameters	5th Characteristic value (MPa)
	Mean	Standard deviation	Mean	Standard deviation		
Cluster 1 (very light species): Ayous (*Triplochiton scleroxylon*) Frake (*Terminalia superba*)	432	71.4	7.42	1.37	Shape: 1.153 Scale: 1.833 Threshold: 5.665	5.80
Cluster 2 (light species): Abura (*Mitragyna cyliata*) Movingui (*Distemonanthus benthamianus*) Dabema (*Piptadeniastrum africanum*)	593	73	10.94	2.55	Shape: 1.450 Scale: 4.052 Threshold: 7.258	7.78
Cluster 3 (medium heavy species): Bilinga (*Nauclea diderrichii*) Doussie (*Afzelia africana*) Padouk (*Pterocarpus soyauxii*) Difou (*Morus mesozygia*)	777	66	14.14	2.44	Shape: 7.772 Scale: 16.67 Threshold: -1.510	9.87
Cluster 4 (heavy species): Azobe (*Lophira alata*) Tali (*Erythrophleum ivorense*) Okan (*Cylicodiscus gabunensis*)	941	69	18.11	2.65	Shape: 3.052 Scale: 8.273 Threshold: 10.73	13.86

Padouk, and Doussie; cluster 4 (heavy hardwoods): Azobe, Tali, and Okan. The shear strength characteristics of these clusters are presented in table V. The shear strength means varied from 7.42 MPa (cluster 1) to 18.42 MPa (cluster 4). The box plots of the shear clusters are illustrated in figure 6. The ANOVA resulted in a p-value less than 0.05 (table VI). Thus, the null hypothesis "the shear strength means of the clusters are equal" was rejected. Practically, we can conclude that at least one the shear clusters is different from the others. The results of the Tukey HSD test revealed that each cluster is significantly different from the other cluster, with an

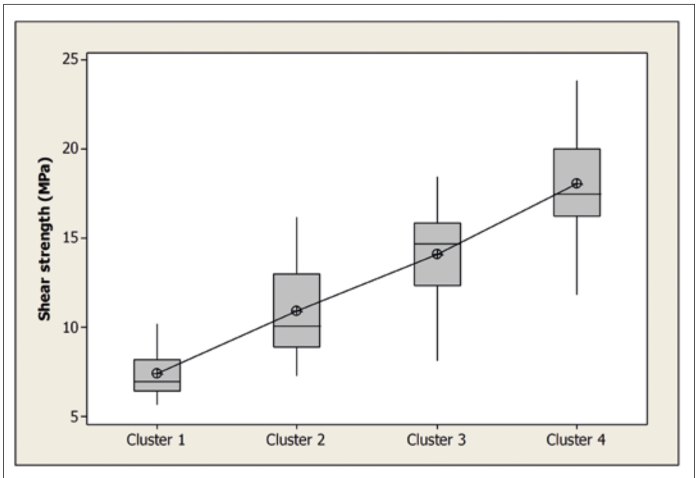

Figure 6.
Box plots of the shear clusters. Cluster 1 (very light species): Ayous (*Triplochiton scleroxylon*), Frake (*Terminalia superba*). Cluster 2 (light species): Abura (*Mitragyna cyliata*), Movingui (*Distemonanthus benthamianus*), Dabema (*Piptadeniastrum africanum*). Cluster 3 (medium heavy species): Bilinga (*Nauclea diderrichii*), Doussie (*Afzelia africana*), Padouk (*Pterocarpus soyauxii*), Difou (*Morus mesozygia*). Cluster 4 (heavy species): Azobe (*Lophira alata*), Tali (*Erythrophleum ivorense*), Okan (*Cylicodiscus gabunensis*).

Table VI.
Results of the ANOVA for the shear clusters.

Source	DF	SS	MS	F value	p-value
Factor	3	2,900.30	966.77	167.95	0.000
Error	223	1,283.67	5.76		
Total	**226**	**4,183.98**			

DF: degrees of freedom; SS: sum of squares; MS: mean squares.

error rate of 1.04%, less than the 5% significance level. Table VII shows the results of the GOF tests. In each cluster, the Weibull, log-normal, and normal distributions do not fit properly the experimental data. Indeed, the Weibull distribution is only accepted in cluster 3, while the log-normal is useful only in cluster 1. The normal distribution is accepted in clusters 3 and 4 and rejected in the other clusters. Such a trend was not observed concerning the 3-parameter Weibull distribution. That distribution fits experimental data well in each cluster (figure 7).

Table VII.
Results of the Anderson-Darling test.

Distribution	Cluster 1			Cluster 2			Cluster 3			Cluster 4		
	AD	p-value	Decision	AD	p-value	Decision	AD	p-value	Decision	AD	p-value	Decision
3-parameters Weibull	0.588	0.133	accepted	0.795	0.042	accepted	0.435	0.211	accepted	0.656	0.063	accepted
Weibull	1.626	< 0.010	rejected	2.431	< 0.010	rejected	0.457	> 0.250	accepted	1.258	< 0.010	rejected
Exponential	10.774	< 0.003	rejected	16.551	< 0.003	rejected	23.959	< 0.003	rejected	19.688	< 0.003	rejected
Normal	1.314	< 0.005	rejected	2.326	< 0.005	rejected	0.814	0.034	accepted	0.760	0.045	accepted
Lognormal	0.841	0.027	accepted	1.553	< 0.005	rejected	1.459	< 0.005	rejected	0.480	0.226	accepted

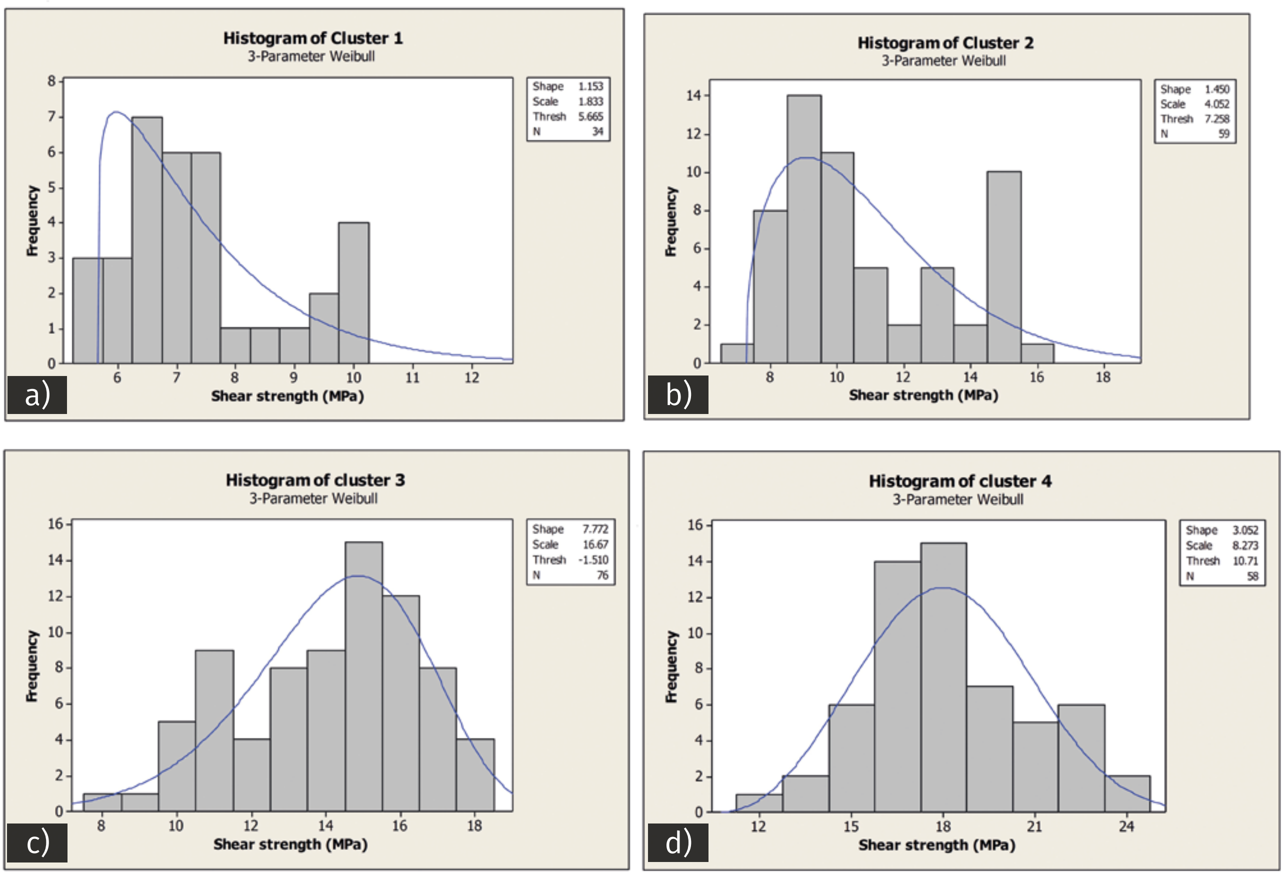

Figure 7.
Illustration of the statistical modelling of the shear strength with the histograms and 3-parameter Weibull modelling of: a) Cluster 1 (very light species): Ayous (*Triplochiton scleroxylon*), Frake (*Terminalia superba*). b) Cluster 2 (light species): Abura (*Mitragyna cyliata*), Movingui (*Distemonanthus benthamianus*), Dabema (*Piptadeniastrum africanum*). c) Cluster 3 (medium heavy species): Bilinga (*Nauclea diderrichii*), Doussie (*Afzelia africana*), Padouk (*Pterocarpus soyauxii*), Difou (*Morus mesozygia*). d) Cluster 4 (heavy species): Azobe (*Lophira alata*), Tali (*Erythrophleum ivorense*), Okan (*Cylicodiscus gabunensis*).

Discussion

The shear strength of wood must be considered in the design of wood structures (Hernandez and Almeida 2003). The shear strength parallel to grain is especially important since it is used to determine dimensions of wood structures. This study provides a preliminary qualification framework of the shear strength, adapted to the high diversity of timber species from the Congo Basin. Such a framework is specified according to two important points: the regression and the probabilistic modelling.

Concerning the first point, this study was conducted using a good diversity of the Congo Basin timbers, represented by 12 species with very different properties, from the least dense to the densest (table I). The difference between the species is confirmed by the ANOVA test. For each species (table IV). The comparison between our results and some available bibliographic values of the ultimate shear-strength parallel to the grain is presented in table II. These bibliographic values were provided while describing the properties of some timber species from the Congo Basin in the Prota4U database (Ayarkwa and Owusu 2008; Bosu and Krampah 2005; Doumenge and Séné 2012; Nyunai Nyemb 2011; Opuni-Frimpong and Opuni-Frimpong 2012; Owusu and Louppe 2012; Gérard and Louppe 2011; Sosef et al. 1995; Jiofack Tafokou 2008) and the Forest Products Laboratory (FPL) database of Madison (Green et al. 1999). Our experimental results are in good accordance with these bibliographic results. For instance, the average shear strength of a very light species such as Ayous wood (*T. scleroxylon*, density 383 kg/m^3 at 12% MC, cluster 1) was 6.56 MPa with a standard deviation of 0.57 MPa. Such a result is in accordance with the variation range from 3 to 8 MPa established by Bosu and Krampah (2005). It is also in accordance with the mean value of 6.8 MPa determined by Green et al. (1999). The average shear strength of Doussie (*A. Africana*, density 753 kg/m^3 at 12% MC, cluster 3), 13.33 MPa, is in accordance with the corresponding variation range 7.5-14 MPa, determined by Gérard and Louppe (2011). The global and successful comparison with bibliographic values is an argument for the validation of our experimental results.

The geometric regression provided the most adequate estimation of the shear strength of the timber species (table III). More precisely, that model explained 74% of the total variation of the shear strength (while considering individual specimens) and 81% of the average shear strength variation. Similar results were obtained by Ong (1988) and Green et al. (1999) while investigating the prediction of the shear strength of Malaysian timbers and some hardwood timbers from the Congo Basin at 12% MC, respectively. Ong (1988) found that the proportion of variation explained by the quadratic regression equations, as indicated by the value of R^2, for small clear specimens, was 0.75. However, the other regression models were not tested by these authors. Green et al. (1999) established that the shear strength parallel to the grain of hardwood timbers is correlated with their specific density at 12% MC according to equation 10:

$$\tau_{parallel} = 21{,}900\, G_{12}^{1.13} \qquad \text{(equation 10)}$$

where $G_{12}^{1.13}$ is the specific gravity of timber species and $\tau_{parallel}$ is the shear strength parallel to the grain at 12% MC. The density ρ (kg/m^3) can be expressed as a function of the specific gravity G_m based on volume at H (%) MC according to equation 11 (Green et al. 1999):

$$\rho = 1{,}000\, G_m (1 + H) \qquad \text{(equation 11)}$$

For H = 12%, we found that the shear strength $\tau_{parallel}$ is correlated with the specific gravity $G_{12}^{1.0523}$ according to equation 12:

$$\tau_{parallel} = 16{,}615\, G_{12}^{1.0523} \qquad \text{(equation 12)}$$

One can notice that our results (equation 12) present some similarity with the Madison FPL Madison approach concerning the prediction of the shear strength (equation 10) at 12% MC. We recall that the FPL did not provide a regression coefficient. The differences among the coefficients of these equations may be explained by the high number of timber species investigated by the FPL.

The statistical analysis conducted by Wolenski et al. (2020) revealed that the geometric model provides the best fit for the prevision of the shear strength of Brazilian timbers. Therefore, in practical terms, the geometric regression models obtained in our study and illustrated in figures 4 and 5 can be considered as reference relations that may be successfully used to predict the shear strength by measuring the density of Congo Basin hardwoods. The estimated strength values from these regression equations will enable acceptable comparisons between species (even those that have not yet been investigated) to be made and provide fast and reasonably reliable basic data. Nevertheless, one should always notice that individual species should be tested by a strength testing machine whenever possible, so as to provide more accurate and complete information.

The second point deals with the specification of design parameters, such as the characteristic values. As a prerequisite, one needs to identify the proper probabilistic distribution model for the shear strength. It can be noticed in table VII that the exponential distribution is rejected in each cluster, while the acceptability of Weibull, normal, and log-normal distributions is neither consistent nor stable. The 3-parameter Weibull distribution is better suited to describe the shear failure in each cluster. Hence, all the shear failure of the Congo Basin hardwoods can be modelled by the 3-parameter Weibull distribution, making the model more straightforward. A similar result was obtained by Talla et al. (2005) while analysing the statistical model of *Rafia vinifera L.* (Arecacea), a bamboo species. Such a distribution can be successfully used in forestry applications (Green et al. 1994). The corresponding parameters of that distribution are presented in table V. One can also notice the characteristic values of the shear strength in table V. They are respectively 5.80 MPa (cluster 1), 7.78 MPa (cluster 2), 9.87 MPa (cluster 3) and 13.86 MPa (cluster 4). Although very light species such as Ayous wood and Frake wood (cluster 1) are not generally used for structural applications, their characteristic shear strength values may be used as threshold values in the decision-making process. These values will be useful for the shear design and reliable specifications of wood-based products from the Congo Basin. In a given cluster, different timber species may be used interchangeably without decreasing the quality of the product, specified in this study by the 5th characteristic values. The clustering approach should make it possible to simplify the production of technical information concerning the corresponding timber species. This result constitutes an improvement of the existing information on the shear strength of timber from the Congo Basin at the material scale.

Results of this study may facilitate the decision-making process while designing structural wood-based components, such as glulam and blockboards, using timber species from the Congo Basin. Within a given cluster, several timber species may be interchangeably used without decreasing the quality and integrity of the product. This is an important point concerning the preservation of endangered or over exploited timber species. The results may also be used to improve some tropical databases, such as Tropix 7.5.1, since each timber species may be attached to one quality specification (cluster). They also draw the possibility of reducing sampling costs while investigating the mechanical features of tropical timbers from the Congo Basin. However, their consolidation and implementation will need further investigations by considering more timber species.

Conclusion

The main objective of this study was to specify a preliminary qualification of Congo Basin timber species with regard to shear, in which the variability is considered. The reduction of the variability of that property is a major challenge in construction applications in which similar trends of resistance may be needed. To reach such a goal, 12-timber species with very different properties, from the least dense to the densest, were considered. Their shear strength was determined experimentally at 12% MC, based on European standards specification, at the scale of the wood material. They were derived from clear and defect free specimens. In the first step of our study, we showed that the prediction of the shear strength can be modelled properly using a geometric regression. A similar prevision trend was observed concerning Malaysian timber species. In the second step of our study, we showed that these species may be assigned to four distinct technological clusters, defined by their density range: “very light”, “light”, “medium heavy”, and “heavy”. The difference between clusters was confirmed by the Tukey HSD test. As an effort to develop design stresses aiming at facilitating a decision-making process, the relative Goodness of Fit of five shear strength distributions (normal, log-normal, exponential, 2-parameter Weibull, and 3-parameter Weibull) that are used in wood-related applications was evaluated. The results showed that the three parameter Weibull distribution is well suited compared to the other distributions. The findings of this study provide a new perspective on the various levels of performance with regard to shear, which should be considered when using tropical timber species from the Congo Basin. Potential applications may concern reliable and interchangeable uses in the construction industry and sampling costs reduction for potential testing of structural timbers.

Further research will address the acceptability and implementation of these results by wood industry operators in the African timber sector. More timber species need to be considered to consolidate our results. The specification of the influence of the orthotropic directions of wood, as well as the influence of moisture content on the shear strength, will be needed in order to enrich our results. We also intend to consolidate our results by investigating other shear testing procedures.

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Data access
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References

Aicher S., Ahmad Z., Hirsch M., 2018. Bondline shear strength and wood failure of European and tropical hardwood glulams. European Journal of Wood and Wood Products, 76: 1205-1222. https://link.springer.com/article/10.1007/s00107-018-1305-0

Alves R. C., Motta P. J., Bremer C. F., Mantilla J. N. R., Carrasco E. V. M., 2013. Application of the Non-destructive method of drill resistance for the determination of the strength of Brazilian tropical woods. International Journal of Engineering and Technology IJET-IJENS, 13 (04): 69-73. https://www.researchgate.net/publication/274959989_Application_of_the_Nondestructive_Method_of_Drill_Resistance_for_Determination_of_the_Strength_of_Brazilian_Tropical_Woods

Ayarkwa J., Owusu F. W., 2008. *Cylicodiscus gabunensis* Harms. Record from PROTA4U. In: PROTA (Plant Resources of Tropical Africa / Ressources végétales de l’Afrique tropicale). Louppe D., Oteng-Amoako A. A., Brink M. (eds). Wageningen, Netherlands. www.prota4u.org

Ayina O., 2002. Commentaries, Annals in Civil Engineering Wood, 6: 19-20.

Ayina O., Morlier P., 1998. Modelling the behavior of wood under a constant torque. Materials and Structures, 31: 405-410. https://doi.org/10.1007/BF02480714

Bosu P. P., Krampah E., 2005. *Triplochiton scleroxylon* K. Schum. Record from PROTA4U. In: PROTA (Plant Resources of Tropical Africa/Ressources végétales de l'Afrique tropicale). Louppe D., Oteng Amoako A. A., Brink M. (eds). Wageningen, Netherlands. www.prota4u.org

Bourreau D., Aimene Y., Beauchene J., Thibaut B., 2013. Feasibility of glued laminated timber beams with tropical hardwoods. European Journal of Wood Products, 71: 653-662. https://doi.org/10.1007/s00107-013-0721-4

Brandner R., Schickhofer G., 2015. Probabilistic models for the modulus of elasticity and shear in serial and parallel acting timber elements. Wood science and Technology, 49: 121-146. https://link.springer.com/article/10.1007/s00226-014-0689-1

Castera P., Morlier P., 1994. Variability of the mechanical properties of wood: Randomness and determinism. In: Probabilities and Materials. D. Breysse (ed.). NATO ASI Series (Series E: Applied Sciences), vol. 269 (Dordrecht: Springer). https://doi.org/10.1007/978-94-011-1142-3_12

Chowdhury Md. Q., Sarker S. K., Deb J. C., Sonet S. S., 2014. Timber species grouping in Bangladesh: linking wood properties. Wood Science and Technology. https://doi.org/10.1007/s00226-013-0532-0

Cubberly W. H., 1993. Dictionary of Materials and Testing, Society of Automotive Engineers, Inc., 1993.

Cunha C., Tenorio M., Lima D. F., Reboucas A., Neves L. C., Branco J. M., 2021. Mechanical characterization of Iroko wood using small specimens. Buildings, 11 (3): 116. https://doi.org/10.3390/buildings11030116.

Czmoch I., 2021. Probabilistic modelling of bending strength of timber beams with the help of weak zones model. Periodica Polytechnica Civil Engineering, 65 (4): 1295-1305. https://doi.org/10.3311/PPci.19228

De Melo J. E., Pellicane P. J., de Souza M. R., 2000. Goodness-of-fit analysis on wood properties data from six Brazilian tropical hardwoods. Wood Science and Technology, 34: 83-97. https://doi.org/10.1007/s002260000033

Doumenge C., Séné V. O., 2012. *Lophira alata* Banks ex C.F. Gaertn. In: PROTA (Plant Resources of Tropical Africa/Ressources végétales de l'Afrique tropicale). Lemmens R. H. M. J., Louppe D., Oteng-Amoako A. A. (eds). Wageningen, Netherlands. www.prota4u.org

Eba'a Atyi R., Lescuyer G., Ngouhouo Poufoun J., Moulendè Fouda G., 2013. Étude de l'importance économique et sociale du secteur forestier et faunique au Cameroun. Rapport final. CIFOR.

EN 1052-3:2002, 2003. Methods of Test for Masonry – Part 3: Determination of Initial Shear Strength (Brussels, Belgium: European Committee for Standardization).

EN 392, 1995. Glued laminated timber – Shear tests of glue lines. European Committee for standardization (CEN), Brussels.

FCBA Institute, 2015. Bois massifs Structuraux (Fiches produits ouvrages Bois). FCBA Institute, IRABOIS.

Foschi R. O., 2005. An approach to performance based-design and reliability-based optimization of wood structures. Probabilistic models in timber engineering: tests, models, applications. 8-9 September 2005, Arcachon, France.

Lavalette A., Pommier R., Danis M., Castéra P., 2012. Tension-shear failure criterion for a wood composite designed for shipbuilding applications. World Conference on Timber Engineering. Oakland

Gérard J., Louppe D., 2011. *Afzelia africana* Sm. ex Pers. Record from PROTA4U. In: PROTA (Plant Resources of Tropical Africa / Ressources végétales de l'Afrique tropicale). Lemmens R. H. M. J., Louppe D., Oteng-Amoako A. A. (eds). Wageningen, Netherlands. www.prota4u.org

Green E. J., Roesch F. A., Smith A. F. M., Strawderman W. E., 1994. Bayesian estimation for the three parameter Weibull distribution with tree diameter data. Biometrics. 50 (1): 254-269. https://doi.org/10.2307/2533217

Green D. W., Winandy J. E., Kretschmann J. E., 1999. Mechanical properties of Wood. Chapter 4. In Wood Handbook. 4-1, 4-45. Forest Products Laboratory. Wood handbook – Wood as an engineering material. General Technical ReportsFPL–GTR–113. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, 463 p.

Hernandez R. E., Almeida G., 2003. Effects of wood density and interlocked grain on the shear strength of three Amazonian tropical hardwoods. Wood and Fiber Science, 35 (2): 154-166.

ITTO (International Tropical Timber Organization), 2001. The Tropical Industrial Lesser-Used Wood Species Database. ITTO, Yokohama.

Jiofack Tafokou R. B., 2008. *Piptadeniastrum africanum* (Hook.f.) Brenan. Record from PROTA4U. In: PROTA (Plant Resources of Tropical Africa / Ressources végétales de l'Afrique tropicale) Louppe D., Oteng-Amoako A. A., Brink M. (eds). Wageningen, Netherlands. www.prota4u.org

Khokhar A., Zhang H., Ridley-Ellis D., 2010. The shear strength, and failure modes of timber joists obtained from the torsion test method. WCTE 2010.

Lanvin J. D., Reuling D., Rouger F., van de Kuilen J. W., Ravenshorst G., Reinbold G., et al., 2009. Simplified strength properties assessment for tropical hardwoods in view to CE marking. In: Proceedings of the Second International Scientific Conference on Hardwood Processing, 28-29 September 2009, Paris.

NBR (Norma Brasileira Regulamentadora) 7190, 1997. Design of wooden structures. Rio de Janeiro, Brazil, 107 p.

Ndong-Bidzo C. H., Pambou-Nziengui C. F., Ikogou S., Kaiser B., Moutou Pitti R., 2021. Mechanical properties of glued-laminated timber made up of mixed tropical wood species. Wood Material Science & Engineering. https://doi.org/10.1080/17480272.2021.1960422

NF EN 408+A1, 2012. Structures en bois - Bois de structure et bois lamellé-collé - Détermination de certaines propriétés physiques et mécaniques. European Committee for standardization (CEN), Brussels, 36 p. https://www.boutique.afnor.org/fr-fr/norme/nf-en-408-a1/structures-en-bois-bois-de-structure-et-bois-lamellecolle-determination-de-/fa178999/39837

Nyunai Nyemb, 2011. *Mitragyna stipulosa* (DC.) Kuntze. Record from PROTA4U. In: PROTA (Plant Resources of Tropical Africa / Ressources végétales de l'Afrique tropicale). Lemmens R. H. M. J., Louppe D., Oteng-Amoako A. A. (eds). Wageningen, Netherlands. www.prota4u.org

Ong S. H., 1988. Possibility of predicting Mechanical Strength Properties of Malaysian timbers. Journal of Tropical Forest Science, 1 (4): 318-326.

Opuni-Frimpong N. Y., Opuni-Frimpong E., 2012. *Nauclea diderrichii* (De Wild. & T. Durand) Merr. In: PROTA (Plant Resources of Tropical Africa/Ressources végétales de l'Afrique tropicale). Lemmens R. H. M. J., Louppe D., Oteng-Amoako A. A. (eds). Wageningen, Netherlands. www.prota4u.org

Owusu F. W., Louppe D., 2012. *Distemonanthus benthamianus* Baill. Fiche de PROTA4U. In: PROTA (Plant Resources of Tropical Africa/Ressources végétales de l'Afrique tropicale). Lemmens R. H. M. J., Louppe D., Oteng-Amoako A. A. (eds). Wageningen, Netherlands. www.prota4u.org

Paradis S., Guibal D., Gérard J., Beauchêne J., Brancheriau L., Cabantous B., et al., 2015. Tropix 7.5.1 – Caractéristiques technologiques de 245 essences tropicales et tempérées (Technological Characteristics of 215 Tropical Timbers). Logiciel de gestion de données, version française et anglaise, CIRAD. http://tropix.cirad.fr/, https://doi.org/10.18167/74726F706978

PyoralaJ.,SaarinenN.,KankareN.V.,CoopsN.C.,LiangX.,WangY.M., et al., 2019. Variability of wood properties using airborne and terrestrial laser scanning. Remote Sensing of Environment, 235: 111474.

Ravenshorst G. J. P., Gard W. F., van de Kuilen J. W. G., 2013. The importance of characterisation and sampling of tropical wood species with regard to strength and durability classification. HERON, 58 (2/3): 195-222.

Ravenshorst G., Gamper N., Van De Kuilen J. W. G., de Vries P. 2016. Determination of the shear strength of tropical hardwood timber. In: WCTE 2016 - World Conference on Timber Engineering. Eberhardsteiner J., Winter W., Fadai A., Pöll M. (eds.) Vienna University of Technology, 677-684.

Rodrigues E. F. C., De Araujo V. A., Cavalheiro R. S., Marini L. J., Almeida J. P. B., Azevedo A. R. G., et al., 2023. Influence of growth rings position of wood on the determination of its shear strength parallel to grain. Journal of Materials Research and Technology, 24: 9765-9779. https://www.sciencedirect.com/science/article/pii/S2238785423011602

Romeu J. L., 2003. Anderson-Darling: a goodness of fit test for small samples assumptions. START (Selected Topics in Assurance Related Technologies), 10 (5). https://web.cortland.edu/matresearch/AndrsDarlSTART.pdf

Sallenave P. 1955. Propriétés physiques et mécaniques des bois tropicaux de L'Union française. Nogent-sur-Marne, Centre Technique Forestier Tropical (CTFT), CRC Press, 128 p. https://doi.org/10.18167/agritrop/00359

Sosef M. S. M, Boer E., Keating W. G., Sudo S., Phuphathanaphong L., 1995. Terminalia L. In: Plant resources of South-East Asia no. 5(2). Timber trees: minor commercial timbers. Lemmens R. H. M. J., Soerianegara I., Wong W.C. (eds). Leiden: Backhuys, 474-492.

Talla P. K., Foudjet A., Fogue M., 2005. Statistical model of strength in flexion and size effect on the failure of *Raphia vinifera* L. (Arecacea). Journal of Bamboo and Rattan, 4 (4): 335-342.

Vivien J., Faure J., 1995. Arbres des forêts denses d'Afrique Centrale. Espèces du Cameroun. Ministère des Relations Extérieures, Coopération et Développement, ACCT-Paris, 565 p.

Yusoh A. S., Sabaruddin F. A., Paridah M. T., Seng H. L., Mohd K. A. U. H., Ghani A., et al., 2022. Shear strength and hardness of two tropical wood species as function of heat treatment. Maderas-Cienc Tecnol, 24. http://dx.doi.org/10.4067/s0718-221x2022000100429

Wolensky A. R. V., Peixoto R. G., Fedotova V., Christoforo A. L., Lahr F. A. R., 2020. Shear strength estimation model for tropical wood species. Wood Research, 65 (1): 175-182.

Wong T. M., 2002. A Dictionary of Malaysian Timbers. Revised by Lim S. C., Chung R. C. K., Malayan Forest Record, No. 30. Forest Research Institute Malaysia. Printed in Malaysia by Percetakan Haji Jantan, Kuala Lumpur, Malaysia, 201 p.

Zziwa A., Kaboggoza J. R. S., Mwakali J. A., Banana A. Y., Kyeyune R. K., 2006. Physical and mechanical properties of some less utilized tropical timber tree species growing in Uganda. Uganda Journal of Agricultural Sciences, 12 (1): 57-66.

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DYNAMIQUE DE LA VÉGÉTATION EN SAVANE SOUDANIENNE / RECHERCHE

Dynamique d'occupation et d'utilisation des terres dans la Forêt Classée de Tiogo au Burkina Faso : caractérisation, moteurs et impacts sur la diversité et le stock de carbone ligneux

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Photo 1.
Aperçu de la savane arborée dans la Forêt Classée de Tiogo, Burkina Faso.
Overview of the tree savannah in the Tiogo Forest Reserve, Burkina Faso.
Photo I. Konaté

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RÉSUMÉ

Dynamique d'occupation et d'utilisation des terres dans la Forêt Classée de Tiogo au Burkina Faso : caractérisation, moteurs et impacts sur la diversité et le stock de carbone ligneux

L'état de dégradation des forêts est une préoccupation mondiale particulièrement pour l'Afrique. De ce fait, plusieurs forêts classées sont de plus en plus menacées d'extinction dont les causes sont anthropiques et climatiques. L'étude a évalué la dynamique du couvert végétal et ses implications sur le stock de carbone aérien et la diversité ligneuse de la Forêt Classée de Tiogo au Burkina Faso. Une analyse d'images Landsat des années 1990, 1999, 2009 et 2019, et des données socioéconomiques et d'inventaire forestier ont été combinées dans différentes unités d'occupation des terres : savane arborée, savane arbustive, forêt galerie, cultures pluviales et territoires agroforestiers. Entre 1990 et 2019, 47 % de la superficie des savanes arborées ont été perdus au profit des savanes arbustives et des cultures pluviales et territoires agroforestiers. Les feux de brousse, la coupe du bois et l'activité agricole constituent les principaux facteurs de dégradation. Les valeurs de la diversité ligneuse de la savane arborée (2,14 ± 0,31) et de la savane arbustive (1,92 ± 0,43) étaient plus élevées que celles des cultures pluviales et territoires agroforestiers (1,31 ± 0,62) et de la forêt galerie (0,63 ± 0,41). La forêt galerie avait le plus important potentiel de stock de carbone aérien (35,5 tC/ha), suivi de la savane arborée (7,1 tC/ha), puis de la savane arbustive (2,5 tC/ha) et des cultures pluviales et territoires agroforestiers (1,7 tC/ha). Les changements d'unités d'occupation des terres dans la Forêt Classée de Tiogo ont induit entre 1990 et 2019, une réduction de 41 % du potentiel du stock de carbone aérien. Il en ressort le besoin de promouvoir des alternatives pour les moyens de subsistance et l'énergie pour les ménages, et le renforcement des initiatives de sensibilisation.

Mots-clés : domaine classé, séquestration de carbone, activités humaines, savane soudanienne, changement d'utilisation de terres, moteurs de changement, Burkina Faso.

ABSTRACT

Dynamics of land occupation and use in the Tiogo Forest Reserve in Burkina Faso: characterisation, drivers and impacts on diversity and wood stock

Forest degradation is an issue of global concern, particularly for Africa, where protected forests are under increasing threat of extinction, due to anthropogenic and climatic causes. The aim of this study is to assess the dynamics of plant cover and its implications for above-ground carbon stocks and woody species diversity in the Tiogo Forest Reserve in Burkina Faso. Analysis of Landsat images from 1990, 1999, 2009, and 2019, socio-economic data and forest inventories were combined in different land-use units: wooded savannah, shrub savannah, gallery forest, rainfed crops and agroforestry areas. Between 1990 and 2019, 47% of the tree savannah area was lost to shrub savannah, rainfed crops and agroforestry. Bush fires, wood cutting and agricultural activities are the main factors contributing to this degradation. The wood diversity values for tree savannah (2.14 ± 0.31) and shrub savannah (1.92 ± 0.43) were higher than for rainfed crops, agroforestry areas (1.31 ± 0.62) and gallery forest (0.63 ± 0.41). Gallery forest had the greatest potential for aboveground carbon storage (35.5 tC/ha), followed by tree savannah (7.1 tC/ha), then shrub savannah (2.5 tC/ha) and rainfed crops and agroforestry areas (1.7 tC/ha). Between 1990 and 2019, changes in land use units in the Tiogo Forest Reserve resulted in a 41% reduction in the potential for aboveground carbon storage. There is a need to promote alternatives for livelihoods and energy for households, and to strengthen awareness-raising initiatives.

Keywords: conservation area, carbon sequestration, human activities, Sudanian savannah, land use change, drivers of change, Burkina Faso.

RESUMEN

Dinámica de ocupación y de utilización de las tierras en el bosque catalogado de Tiogo, en Burkina Faso: caracterización, motores e impacto en la diversidad y el stock de carbono leñoso

El estado de degradación de los bosques es una preocupación mundial, y particularmente para África. Por ello, varios bosques catalogados tienen cada vez más amenazas de extinción por causas antrópicas y climáticas. El estudio evaluó la dinámica de la cubierta vegetal y sus implicaciones en el stock de carbono aéreo y la diversidad leñosa del bosque catalogado de Tiogo, en Burkina Faso. Análisis de imágenes Landsat de los años 1990, 1999, 2009 y 2019, datos socioeconómicos e inventarios forestales se combinaron en diferentes unidades de ocupación de las tierras: sabana arbórea; sabana arbustiva; bosque en galería, y cultivos pluviales y territorios agroforestales. Entre 1990 y 2019, el 47 % de la superficie de las sabanas arbóreas se perdió convirtiéndose en sabanas arbustivas, cultivos pluviales y territorios agroforestales. Los fuegos de matorral, la tala del bosque y la actividad agrícola constituyen los principales factores de degradación. Los valores de la diversidad leñosa de la sabana arbórea (2,14 ± 0,31) y de la sabana arbustiva (1,92 ± 0,43) eran más elevados que los de los cultivos pluviales y territorios agroforestales (1,31 ± 0,62) y del bosque en galería (0,63 ± 0,41). El bosque en galería tenía el potencial de stock de carbono más importante (35,5 tC/ha), seguido por la sabana arbórea (7,1 tC/ha), luego por la sabana arbustiva (2,5 tC/ha) y finalmente por los cultivos pluviales y territorios agroforestales (1,7 tC/ha). Los cambios de unidades de ocupación de las tierras en el bosque catalogado de Tiogo indujeron entre 1990 y 2019, una reducción del 41 % del potencial de stock de carbono aéreo. Aquí resalta la necesidad de promover alternativas para los medios de subsistencia y la energía para los hogares, y reforzar las iniciativas de sensibilización.

Palabras clave: dominio catalogado, secuestro de carbono, actividades humanas, sabana sudanesa, cambio de uso de las tierras, motores de cambio, Burkina Faso.

Introduction

Les écosystèmes forestiers sont déterminants dans la recherche de solutions aux problèmes majeurs de l'humanité. En effet, les forêts constituent des puits de carbone naturels indispensables à la réduction des émissions de gaz à effet de serre et contribuent aussi à la lutte contre l'insécurité alimentaire et la pauvreté (Kristensen et Balslev, 2003 ; FAO, 2016). Cependant, la régression des superficies forestières est une contrainte majeure à l'expression de ce potentiel des forêts. En effet, à l'échelle mondiale, le couvert forestier a régressé de 7,8 millions d'hectares entre 1990-2000, 5,2 millions entre 2000 et 2010 et 4,7 millions par an entre 2010 et 2020 (FAO, 2020). Sur les six régions du monde, l'Afrique, notamment la partie occidentale, est celle qui a le plus perdu de superficies forestières avec un taux de régression de 0,45 % par an pour la période de 2000 à 2010 et de 0,59 % entre 2010 et 2020 (FAO, 2020). Il y a donc urgence à mettre en œuvre des stratégies pour faire face à ce phénomène. Cela a donc motivé les décideurs de plus de 140 pays, lors de la 26ème Conférence des Parties (COP) de la Conférence des Nations Unies sur les changements climatiques (CCNUCC) à Glasgow, à faire une déclaration sur les forêts et l'utilisation des terres (FAO, 2021). Dans cette déclaration, les dirigeants promettent de renforcer leurs efforts communs pour, entre autres, conserver les forêts et les autres écosystèmes terrestres et accélérer leur restauration d'ici 2030.

La perte du couvert végétal est une problématique majeure à traiter pour certains pays comme le Burkina Faso qui, déjà, disposent peu de cette ressource naturelle (le couvert végétal est de 14 % de sa superficie totale). Le pays a perdu 59 900 ha/an (soit 1 %) de sa couverture végétale entre 1990 et 2015 (FAO, 2016). Les statistiques montrent aussi que le couvert forestier national est passé de 6 716 500 ha en 2010 à 6 216 400 ha en 2020, soit une régression de 7,44 % (FAO, 2020). Les actions anthropiques, notamment l'agriculture, les feux incontrôlés, la coupe de bois, le surpâturage et l'exploitation minière, sont les principales causes directes de dégradation des ressources forestières (Savadogo, 2007 ; FAO, 2021 ; Ouattara *et al.,* 2022).

À ces actions anthropiques, il faut ajouter les changements et variabilités du climat, notamment les sécheresses qui contribuent à accentuer la régression du couvert forestier (Gansaonré *et al.,* 2020 ; Ouattara *et al.,* 2022). Jadis à l'époque coloniale, dans le souci de conserver la nature (biodiversité végétale et animale) sous pression des actions anthropiques, l'administration coloniale avait procédé à la création des domaines classés dans de nombreux pays en Afrique sub-Saharienne. Ces actes de classement, censés soustraire ces aires protégées de l'emprise humaine et permettre un meilleur développement de la végétation, ne semblent pas être efficaces même s'il existe peu de données quantitatives (Tankoano *et al.,* 2016). Par ailleurs, les études sur les changements d'unités d'occupation des terres font rarement le lien avec leurs implications sur les stocks de carbone.

L'objectif principal de cette étude est d'analyser la dynamique du couvert végétal de la Forêt Classée de Tiogo (Burkina Faso). Spécifiquement, il s'est agi : (i) d'analyser les changements des différentes unités d'occupation des terres en 30 ans ; (ii) de déterminer les moteurs de ces changements ; (iii) d'évaluer la diversité et la séquestration du carbone ligneux par type d'unité d'occupation des terres. Nous avons supposé que : (i) le statut classé de cette forêt n'a pas suffi à la protéger des actions anthropiques et qu'elle s'est dégradée ; (ii) les changements d'unités d'occupation des terres ont conduit à des pertes substantielles de stock de carbone aérien.

Photo 2.
Aperçu de la savane arbustive dans la Forêt Classée de Tiogo, Burkina Faso.
Overview of the shrub savannah in the Tiogo Forest Reserve, Burkina Faso.
Photo I. Konaté.

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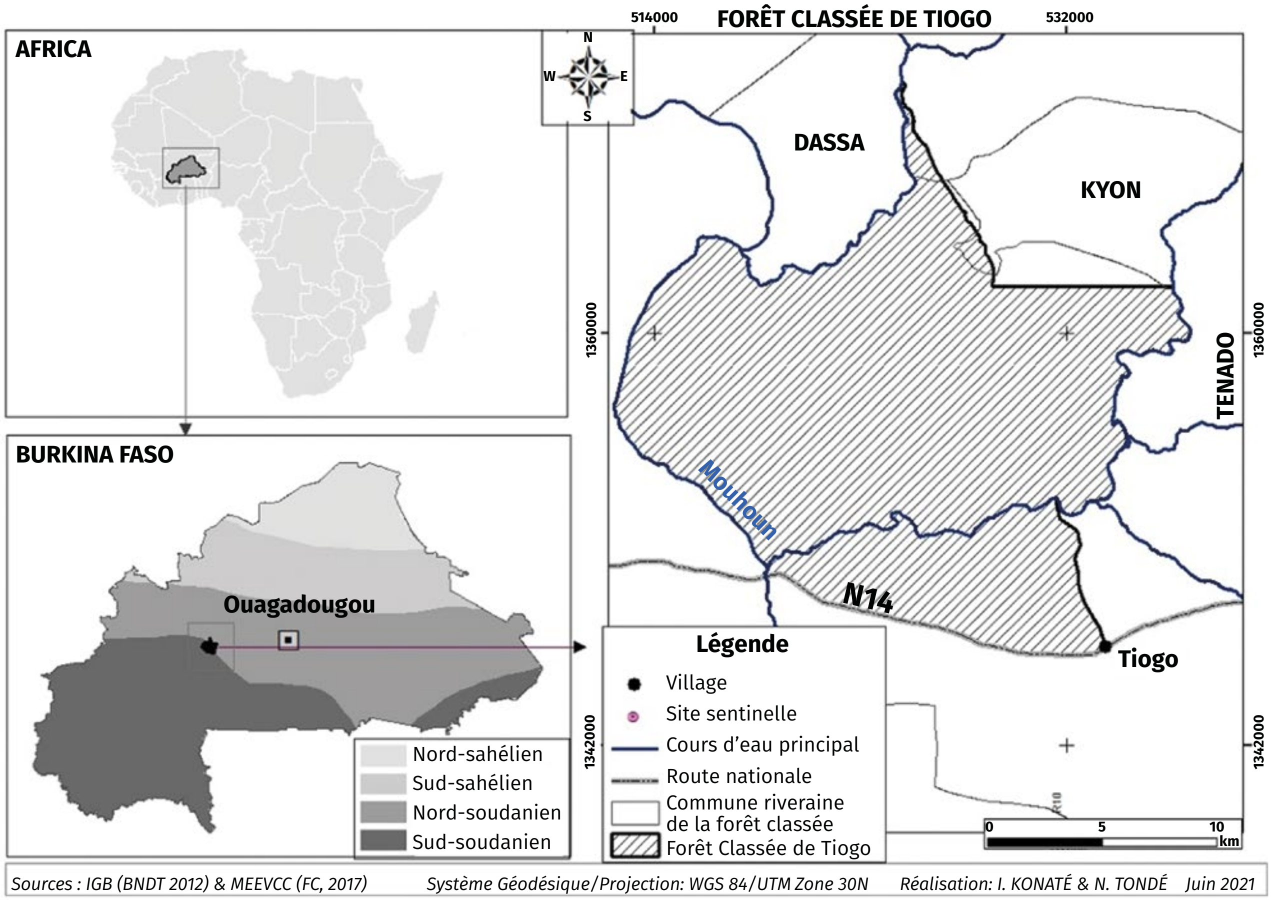


Figure 1.
Localisation du site d'étude (la Forêt Classée de Tiogo, Burkina Faso).
Location of the study site (Tiogo Forest Reserve, Burkina Faso).

Matériel et méthodes

Zone d'étude

La Forêt Classée de Tiogo (FCT), de coordonnées géographiques 2°39' et 2°52' longitude ouest et 12°11' et 12°24' latitude nord, se situe dans les départements de Kyon et Ténado, Province du Sanguié, région du Centre Ouest du Burkina Faso. Classée par arrêté n° 114/SE du 17 janvier 1940, elle couvre une superficie d'environ 30 000 ha (figure 1). Au cinquième recensement général de la population en 2019, la commune de Ténado comptait 60 190 habitants, tandis que celle de Kyon en comptait 24 484 pour un taux d'accroissement de 2,6 % (INSD, 2022).

Les types physionomiques de végétation dominants dans la forêt sont la savane arborée (photo 1), la savane arbustive (photo 2), les forêts galeries (photo 3) et les parcs agroforestiers (photo 4) (Sawadogo, 2009).

La Forêt Classée de Tiogo relève de la zone phytogéographique Nord-soudanienne (Fontès et Guinko, 1995), comprise entre les isohyètes de 600 mm et 900 mm et caractérisée par l'alternance de deux saisons, une saison pluvieuse de mai à octobre et une saison sèche de novembre à avril. Entre 2001 et 2020, la pluviosité annuelle moyenne a été de 867 ± 128 mm avec de fortes variabilités interannuelles (DRAAH, 2020). L'année 2012 a été la plus pluvieuse avec 1 117 mm alors que l'année 2017 a été la moins pluvieuse avec 683 mm.

Le relief de la FCT est plat et monotone dans l'ensemble avec quelques buttes cuirassées. L'altitude moyenne est de 300 m au-dessus du niveau de la mer (DRAAH, 2020). Selon Sawadogo (2009), les principaux types de sols sont :

- les sols peu évolués : sols sablo-argileux ou gravillonnaires en surface, gravillonnaires en profondeur reposant le plus souvent sur une cuirasse et/ou carapace ;
- les sols hydromorphes, profonds constitués d'argile et de sable ;
- les sols à sesquioxydes de fer (ou oxyde ferrique, Fe_2O_3, couramment nommés sols ferralitiques) dont la profondeur est variable.

Méthodes d'évaluation de la dynamique spatio-temporelle de la végétation et d'identification des moteurs de cette dynamique

Evaluation de la dynamique spatio-temporelle de la végétation

• Choix et acquisition des images

Dans le but d'évaluer la dynamique spatio-temporelle de la Forêt Classée de Tiogo (FCT) entre 1990 et 2019, des images satellitaires de type Landsat, prises à quatre dates différentes (1990, 1999, 2009 et 2019), ont été utilisées pour effectuer une analyse diachronique de la dynamique de l'occupation et d'utilisation des terres. Le choix de ce type image se justifie par sa disponibilité à titre gratuit et de sa résolution spatiale élevée (Dimobe *et al.,* 2017 ; Soulama *et al.,* 2015 ; Ganamé, 2021). Ces quatre images satellitaires provenant de la scène *Path* (Colonne) 196 ; *Row* (Ligne) 051 (Tankoano *et al.,* 2016) et de résolution spatiale 30 m × 30 m ont été prises au début de la saison sèche entre les mois d'octobre et de novembre. Elles sont issues du capteur de TM (Thematic Mapper) de Landsat 5 d'octobre 1990, du capteur Landsat 7 ETM+ (Enhanced Thematic Mapper Plus) d'octobre 1999, du capteur Landsat 7 ETM+ de novembre 2009 et du capteur 8 OLI-TIRS (Operational Land Imager) de novembre 2019. Le choix de la période (début de saison sèche) d'acquisition des images permet d'avoir une différenciation maximale des unités d'occupation des terres (Dimobe *et al.,* 2017 ; Belem *et al.,* 2018 ; Gansaonré *et al.,* 2020 ; Ganamé, 2021). En effet, à cette période, dans la zone soudanienne, les prises de vue ont l'avantage d'avoir un très faible taux de couverture nuageuse et de réduire les problèmes liés aux différences d'angles solaires, aux changements phénologiques de la végétation et à la différence d'humidité des sols (Tankoano *et al.,* 2016 ; Ganamé, 2021). Ces images utilisées ont été téléchargées sur le site web de *United States Geological Survey*[1]. Ensuite, l'extraction de la zone de travail a été découpée sur chaque image des 4 dates. Cela a été opéré avant d'aborder les étapes de prétraitement et de traitement des images réalisées à l'aide du logiciel de télédétection ENVI 5.3.

• Prétraitement des images

C'est une opération préliminaire de traitement qui permet la normalisation des images acquises (Ezzine *et al.,* 2012). Elle comporte les différentes corrections géométriques et radiométriques et permet aussi d'éliminer les effets perturbateurs atmosphériques. Les images satellitaires utilisées dans le cadre de l'étude avaient déjà subi des opérations de géoréférencement (corrections géométriques) par le fournisseur avant leur mise en ligne sur le site de téléchargement. Les corrections dans la présente étude étaient donc liées aux perturbations radiométriques et atmosphériques aussi appelées étalonnages d'images.

Photo 3.
Aperçu d'une galerie forestière dans la Forêt Classée de Tiogo, Burkina Faso.
Overview of a forest gallery in the Tiogo Forest Reserve, Burkina Faso.
Photo I. Konaté.

Photo 4.
Cultures pluviales et territoires agroforestiers dans la Forêt Classée de Tiogo, Burkina Faso.
Rainfed crops and agroforestry areas in the Tiogo Forest Reserve, Burkina Faso.
Photo I. Konaté.

[1] https://earthexplorer.usgs.gov

Elles ont été effectuées grâce à la commande « *Landsat calibration* » de l'outil ENVI. Cela a permis de : (i) corriger les effets des différents artefacts qui perturbent la mesure radiométrique, notamment les défauts du capteur et le voile atmosphérique ; (ii) débarrasser le rayonnement de tous les effets atmosphériques ; (iii) convertir les radiances en réflectances ; (iv) harmoniser les luminances au sol et rendre comparables les images acquises malgré des périodes et des conditions climatiques variées (Chekchek et Fennouh, 2019). Le prétraitement a visé aussi à effectuer les compositions colorées sur toutes les images des 4 dates, dont l'objectif est de permettre une bonne discrimination visuelle des différentes unités d'occupation des terres en tenant compte des signatures spectrales en présence. Pour l'image de 2019, une composition dite de fausses couleurs à partir des bandes proche infra-rouge, verte et bleue (5-4-3) a été réalisée. Pour les images de 2009, 1999 et 1990, les compositions dites de fausses couleurs ont été obtenues à partir des bandes rouge, verte et bleue (4-3-2). Ces compositions colorées s'appuient sur les propriétés de la végétation qui lui permettent de réfléchir très fortement le rayonnement proche infrarouge et faiblement le rayonnement vert lors du processus de photosynthèse. Elles mettent en évidence facilement la présence de végétation vivante.

À partir des compositions colorées, des unités homogènes d'occupation des terres ont ensuite été délimitées sur la base d'une interprétation visuelle (photo-interprétation) des signatures spectrales observées sur l'image la plus récente (2019).

• *Données de vérification terrain*

La détection précise des différentes unités d'occupation des terres demeure difficile à partir des seules images satellitaires et il est donc nécessaire de se pencher sur des données de vérification terrain (Ganamé, 2021). Cette opération consiste à vérifier et identifier sur le terrain la répartition des unités d'occupation des terres délimitées sur la base de la photo-interprétation afin de mieux les discriminer en fonction des différentes signatures spectrales. Ainsi, il a été produit des points de vérification terrain répartis par unité d'occupation des terres sur l'image la plus récente (2019). Les différentes unités d'occupation des terres ont été définies sur la Base de l'Occupation des Terres (BDOT) du Burkina Faso (MEEVCC, 2020). Sur douze unités d'occupation des terres définis dans le cadre de la production de la BDOT de la zone d'étude (tableau I), six classes thématiques ont été retenues sur la base de la photo-interprétation. Cela est dû à des ressemblances d'ordre

Tableau I.
Description des différentes unités d'occupation de terres selon la nomenclature de la Base de Données de l'Occupation des Terres du Burkina Faso de la zone d'étude (MEEVCC,2020).
Description of the different land use units according to the nomenclature of the Burkina Faso Land Use Database for the study area (MEEVCC, 2020).

Unités d'occupation des terres	Caractéristiques
Forêt claire	Peuplement ouvert d'arbres avec un recouvrement compris entre 50 et 70 %, dont les cimes sont plus ou moins jointives ; l'ensemble du couvert demeure clair.
Forêt galerie	Formation forestière tributaire des cours d'eau. Les cordons ripicoles arborés situés le long des cours d'eau à écoulement temporaire ou permanent sont inclus dans cette classe. Elle est généralement dominée par des grands arbres dont la hauteur dépasse très souvent 12 m.
Savane arborée	Les strates arborée et arbustive sont disséminées parmi le tapis herbacé ; l'ensemble a un recouvrement compris entre 20 et 50 % avec une strate arborée supérieure à 10 % mais inférieure à 50 %.
Savane arbustive et herbeuse	Formation herbeuse comportant une strate graminéenne continue d'au moins 80 cm de hauteur. Cette classe se caractérise par des arbustes disséminés parmi le tapis herbacé avec un taux de recouvrement inférieur à 50 % et par une strate arborée inférieure à 10 %.
Plantations forestières et vergers	Plantations d'arbres pour la production de bois, de produits forestiers non ligneux ou pour la régénération du milieu. Les grandes plantations monospécifiques forestières sont incluses dans cette classe.
Zones de culture pluviales et territoires agroforestiers	Zones dans lesquelles les espèces ligneuses sont sélectionnées et préservées sur les terres agricoles à cause des produits et services qu'elles procurent aux communautés locales. Les jeunes jachères sont comprises dans cette classe.
Cultures irriguées	Superficies aménagées et souvent consacrées à la riziculture et à d'autres cultures lors de la contre saison : haricots, niébé, cultures maraîchères…
Zones humides	Les zones humides naturelles comportent les fleuves, cours d'eau, lacs, rivières, mares, plaines d'inondation et bas-fonds. Les zones humides artificielles sont les retenues d'eau de barrages (grands et petits réservoirs), les boulis (mares artificielles) et les terres agricoles irriguées.
Surface en eau	Formation constituée des surfaces en eau
Sols nus, dénudés, cuirassés	Les arbres, arbustes et la strate herbacée sont généralement absents.
Roche nue	Formation composée avec les éboulis, la falaise, les rochers, les affleurements rocheux et les laves.
Habitat	Formation correspondant à l'habitat humain et aux autres établissements humains.

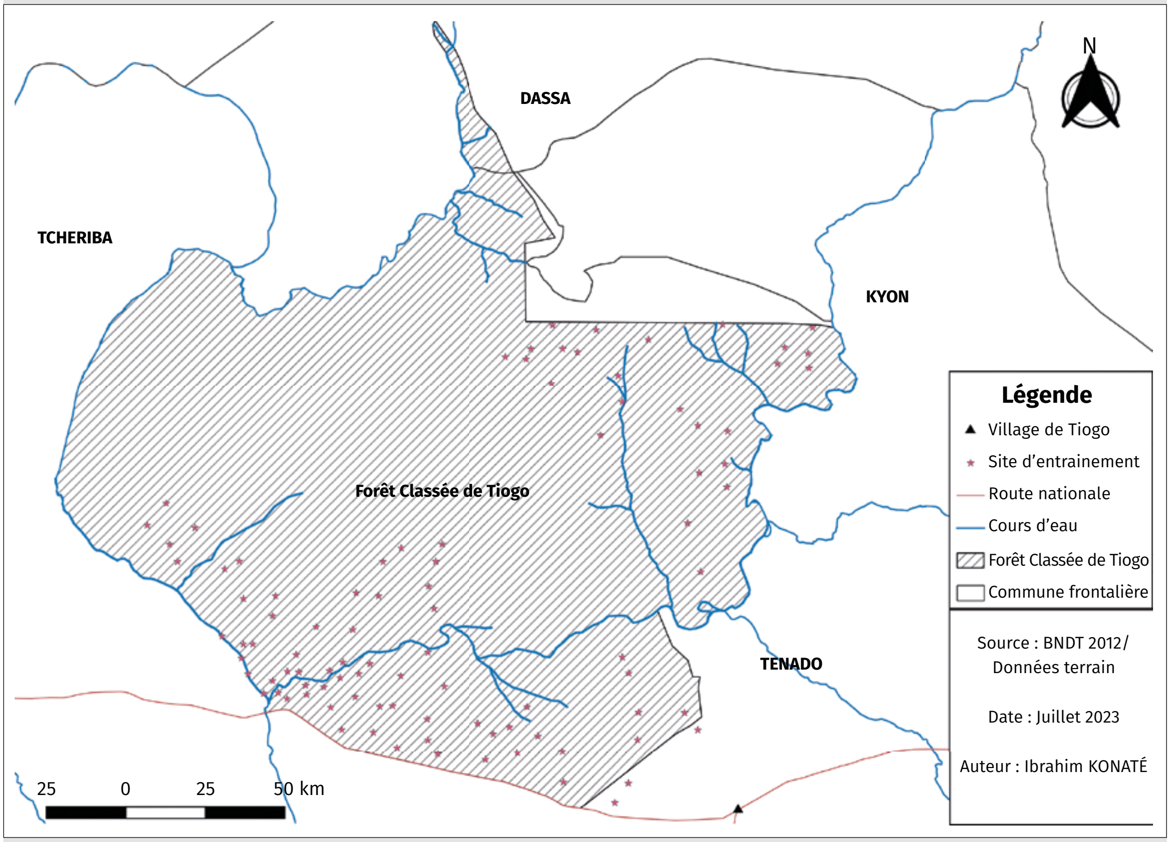


Figure 2.
Répartition des points de vérification terrain à l'échelle de la Forêt Classée de Tiogo, Burkina Faso.
Distribution of field verification points throughout the Tiogo Forest Reserve, Burkina Faso.

physionomique liées à la confusion des signatures spectrales entre certains types d'occupation des terres dans la savane soudanienne (Dimobe, 2017 ; Ganamé, 2021). La forêt galerie, la savane arborée, la savane arbustive, les cultures pluviales et territoires agroforestiers, les sols nus et les cours d'eau ont donc été retenus. Au total, les coordonnées géographiques de 96 points ont été générées (figure 2). Le nombre de points de vérification terrain de la forêt galerie, de la savane arborée, de la savane arbustive, des cultures pluviales et territoires agroforestiers, des sols nus et des cours d'eau s'établit respectivement à : 7 ; 25 ; 32 ; 13 ; 7 ; 5. En outre, sept sites ont été accordés aux unités d'occupation des terres pour lesquelles la composition colorée n'avait pas permis de bien les caractériser. Les coordonnées de ces points ont ensuite été enregistrées dans l'appareil de géo-positionnement GPS (*Global Positionning System*) et permettant d'accéder aux sites sur le terrain où des vérifications ont été effectuées pendant la période du 5 au 8 mars 2021, en vue de s'assurer de l'exactitude des unités d'occupation des terres observées. Il a été supposé qu'entre 2019, date de l'image la plus récente, et 2021, date de la vérification terrain, il n'y a pas eu de changement majeur d'occupation des terres, à cause de conditions environnementales difficiles dans la zone d'étude (climat, sol, etc.).

• *Classification des images*

Les vérifications menées sur le terrain ont conduit à une meilleure connaissance des unités d'occupation générées par la photo-interprétation. Cela a permis de faire les différentes classifications par la méthode supervisée en utilisant l'algorithme « Maximum de vraisemblance » (*Maximum Likelihood*, en anglais). Selon plusieurs auteurs, cet algorithme est performant dans la classification des images, notamment dans les savanes soudaniennes (Dimobe, 2017 ; Belem *et al.*, 2018 ; Ganamé, 2021). En prélude à cette classification, nous avons créé des zones d'entrainements (témoins) communément appelées « Régions d'intérêt » (*Region Of Interest*, en anglais) et abrégées « ROIs » (Dimobe *et al.*, 2017 ; Ganamé, 2021). Ces ROIs au nombre de 24, soit quatre zones par unité d'occupation des terres, ont permis d'identifier des classes d'information qui ont ensuite été utilisées pour définir des classes spectrales représentatives de chaque unité d'occupation des terres (Ganamé, 2021). Cependant, par la connaissance du terrain et de la signature spectrale assignée aux unités d'occupation des terres, et pour réduire les confusions d'appartenance des pixels entre les classes, nous nous sommes limités à quatre ROIs par unité d'occupation des terres. La délimitation de ces ROIs a consisté à dessiner des polygones de pixels homogènes par unité d'occupation des terres, en tenant compte des résultats de la vérification terrain réalisée à partir des images de 2019. Ensuite, ces polygones ont été sauvegardés comme des couches d'information vectorielle, utilisées comme paramètre pour la classification (Dimobe, 2017). L'outil *Google Earth* et les mosaïques d'images des unités d'occupation des terres de l'année 2019 ont servi à mieux définir les ROIs. Pour les années antérieures (1990, 1999 et 2009), pendant la production des ROIs, une observation particulière a été faite sur les changements liés aux différences spatio-temporelles de ces années. Ainsi, les ROIs avec les groupes de pixels inchangés ont été principalement sélectionnés afin de confirmer une équivalence des unités d'occupation des terres entre les années antérieures et l'année récente (2019).

• *Vérification de la précision de la classification*

Pour définir le niveau de précision de la classification, la moitié des ROIs représentants l'ensemble des classes thématiques a été utilisée pour effectuer un test de validation. L'utilisation de la moitié des ROIs pour le test de validation est due aux types d'images utilisées (images Landsat) qui ont des résolutions de 30 m (pas très précises), ce qui ne facilite pas l'identification à 100 % des unités d'occupation des terres. Cela nous a permis de minimiser les erreurs de confusion sur les unités, tout en ayant une précision acceptable. Le résultat du test a donné la matrice de confusion pour chacune des quatre images (1990, 1999, 2009 et 2019) (annexes 6 à 9). La matrice de confusion est un outil restitué sous forme de tableau permettant d'évaluer la fiabilité de la classification (Belem *et al.,* 2018). Elle a permis de déterminer l'erreur de commission et l'erreur d'omission afin d'évaluer la précision globale, et l'indice Kappa (K) évaluant la différence entre modèle prédit et réalité. L'erreur de commission est l'affectation d'un pixel à une classe autre que celle à laquelle il devrait appartenir. L'erreur d'omission, quant à elle, représente la non-affectation d'un pixel à la classe à laquelle elle devrait appartenir (Akoguhi *et al.,* 2022). L'indice Kappa est le rapport entre le nombre de pixels bien classés et le nombre total de pixels sondés. Il évalue la concordance entre les modèles prédits et la réalité (Tilahun et Islam., 2015). Ainsi, le niveau de précision de la classification a été apprécié à partir de la précision globale et de l'indice Kappa (Foody, 2002). Pour ces indicateurs de performance, des valeurs minimales acceptables de 60 % pour la précision (Belem *et al.,* 2018) et de 0,80 à 0,61 pour K (Congalton, 1991) sont requises et ont été retenues.

• *Post classification*

Les images classifiées ont subi une série d'opérations. Il s'agit de la combinaison des classes (*Combine Classes*), du tamisage des classes (*Sieve Classes*), du lissage des classes (*Clump Classes*). À l'issue du processus de lissage, les images classifiées ont été soumises à un filtre majoritaire d'une dimension de 3 × 3 pixels en vue de les rendre plus nettes par élimination des pixels isolés (Tankoano *et al.*, 2016). Les images classifiées et filtrées ont été vectorisées pour passer d'un fichier EVF (fichier image du logiciel ENVI) à Shapefile (fichier d'information vectoriel utilisable dans un logiciel de système d'information géographique, SIG). Cette opération a rendu possible leur exportation dans un logiciel de cartographie Arc GIS 10.5 à partir duquel les cartes d'occupation des terres de 1990, 1999, 2009 et 2019 ont été élaborées. De même, les informations relatives à la variation des superficies des unités d'occupation des terres y ont été déterminées.

La méthodologie adoptée pour la réalisation de ce travail, allant de l'acquisition des images satellitaires jusqu'à la production finale des cartes, est résumée dans la figure 3.

• *Analyse des évolutions du couvert végétal*

- Évolution temporelle de l'occupation des terres : Le taux moyen, entre deux périodes, a été déterminé à partir de la formule donnée par Long *et al.* (2007). Elle s'écrit :

$$Ta = \frac{\frac{(A2 - A1) \times 100}{A1}}{T2 - T1} \qquad \text{(équation 1)}$$

avec Ta = taux annuel de changement (%), A1 = superficie de la classe au temps T1, A2 = superficie de la classe au temps T2.

Le taux de changement global des superficies des unités d'occupation des terres entre les années 1990 et 2019 a été déterminé à travers l'équation proposée par Bernier (1992). Elle s'écrit :

$$Tg = \frac{\ln S2 - \ln S1}{(T2 - T1) \times \ln e} \times 100 \qquad \text{(équation 2)}$$

avec Tg = taux de changement global ; S1 = surface d'une classe d'unité de surface au temps T1 ; S2 = superficie de la même classe d'unité de surface au temps T2 ; ln = logarithme népérien et e = base des logarithmes népériens (e = 2,71828).

Les valeurs positives représentent une progression de la superficie de la classe pendant la période analysée, tandis que les valeurs négatives indiquent la perte de surface d'une classe entre les deux dates. Quant aux valeurs proches de zéro, elles expriment une relative stabilité de la classe sur les deux périodes.

- Évolution spatiale de l'occupation du sol : L'analyse de l'évolution spatiale de l'occupation des terres a été réalisée à l'aide de la matrice de transition ou de conversion des types d'occupation du sol tous les dix ans (1990 à 1999, 1999 à 2009 et 2009 à 2019). Cette technique permet de mettre en évidence les différentes formes de conversion qu'ont subies les formations végétales (Zakari *et al.*, 2018) entre deux dates t1 et t2. Elle est obtenue par le croisement des cartes d'occupation du sol de 1990 et 1999, 1999 et 2009, 2009 et 2019. Cela est rendu possible par l'algorithme « *Intersect polygons* » de l'extension *Geoprocessing* du logiciel ArcGIS. La table d'attribut est ensuite exportée vers le tableur Excel (*Table to Excel*) à partir duquel la matrice de transition a été élaborée.

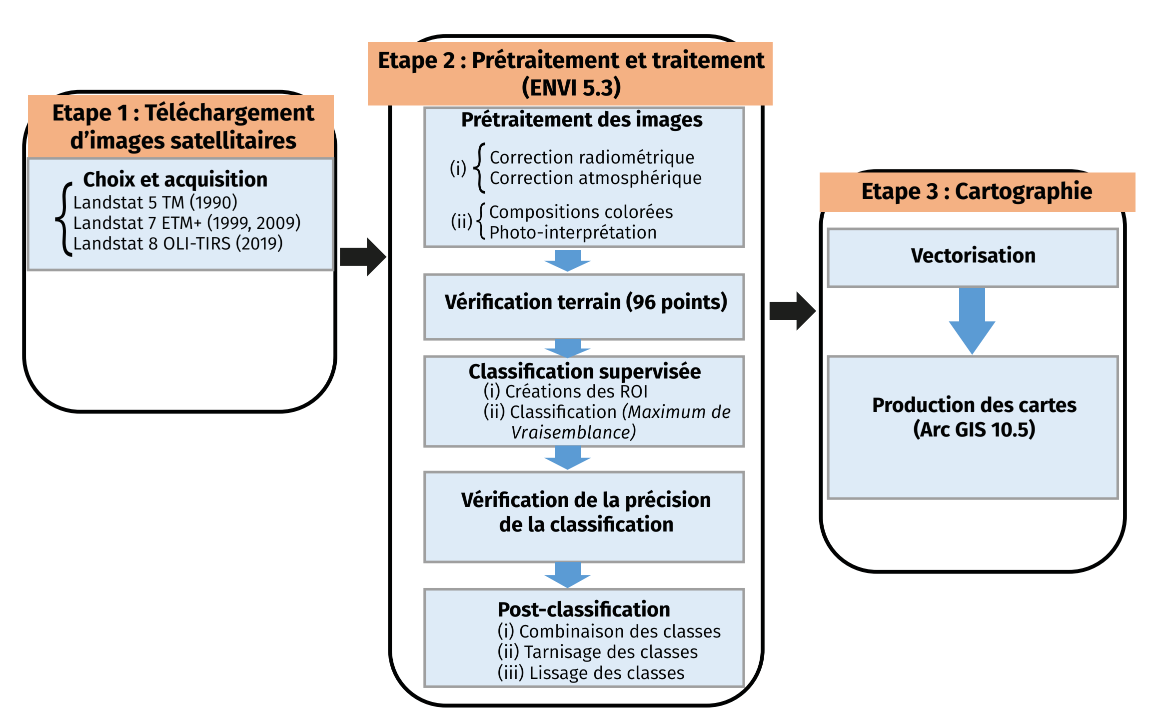


Figure 3.
Schéma méthodologique de l'analyse spatio-temporelle (acquisition, traitements d'images et production des cartes) de la Forêt Classée de Tiogo, Burkina Faso.
Methodology for spatio-temporal analysis (acquisition, image processing and map production) of the Tiogo Forest Reserve, Burkina Faso.

Identification des moteurs de la dynamique spatio-temporelle du couvert végétal

Pour déterminer des facteurs explicatifs des changements observés sur les images traitées, des enquêtes ont été conduites auprès de la population riveraine de la FCT. Elles ont consisté en des entretiens semi-structurés dans 12 villages riverains de la forêt que sont : Esapoun, Tiogo, Tiogo-Mouhoun, Tio, Kyon, Bwo, Négarpoulo, Tialgo, Ziliwélé, Poa, Po et Ténado-Centre. Quatre critères utilisés par Zakari *et al.* (2018) ont guidé le choix de ces villages : la proximité, l'accessibilité, la diversité des groupes socio-professionnels et la diversité des groupes socioculturels. De même, Yelkouni (2004) les a identifiés et considérés dans le cadre de ses enquêtes socio-économiques dans la même zone d'étude. Au total 303 individus ont été enquêtés.

La taille de l'échantillon (N) a été déterminée à partir de la formule de Schwartz (1995) :

$$N = \frac{Z\alpha^2 (P \times Q)}{i^2} \qquad \text{(équation 3)}$$

avec N = taille de l'échantillon ; Zα = 1,96 écart réduit correspondant à un risque α de 5 % ; i = précision désirée (égale à 5 % pour cette étude) ; P = proportion de personnes âgées de plus de 30 ans rapportée à la population totale des trois communes avec Q = 1 - P.

La proportion (P) a été déterminée à partir des données démographiques de 2020 en projection de l'Institut National de la Statistique et de la Démographie (INSD, 2017).

Le nombre de personnes à enquêter par village ($n_{village\ i}$) a été calculé en divisant l'effectif de la population du village par l'effectif total des 12 villages et en multipliant ce nombre par la taille de l'échantillon qui est de 303, soit :

$$n_{village\ i} = \left(\frac{\text{Effectif village } i}{\text{Effectif total des 12 villages}} \right) \times N \qquad \text{(équation 4)}$$

avec N = taille de l'échantillon total.

Les données du cinquième recensement général de la population (RGPH) de 2006 ont servi à évaluer le nombre d'enquêtés par village compte tenu de la non-disponibilité de données projetées en 2020 et désagrégées par village (annexe 1). De même, les résultats obtenus avec le sixième recensement général de la population (RGPH) relatifs aux villages n'étaient pas disponibles en mai 2021 lorsque nous conduisions l'enquête.

Les personnes âgées d'au moins trente (30) ans ont été choisies en supposant leur aptitude à expliquer les changements intervenus au niveau de la FCT (annexe 2). Les investigations ont porté sur :
- les informations générales sur l'enquêté : statut, activités principale et secondaire, tenure foncière (relation à la terre que l'enquêté utilise) ;
- la perception de l'enquêté sur les causes et les facteurs de changement d'utilisation des terres dans la Forêt Classée de Tiogo et sa zone périphérique ;
- les suggestions d'amélioration sur les méthodes de la gestion de la FCT ainsi que le mode de gouvernance.

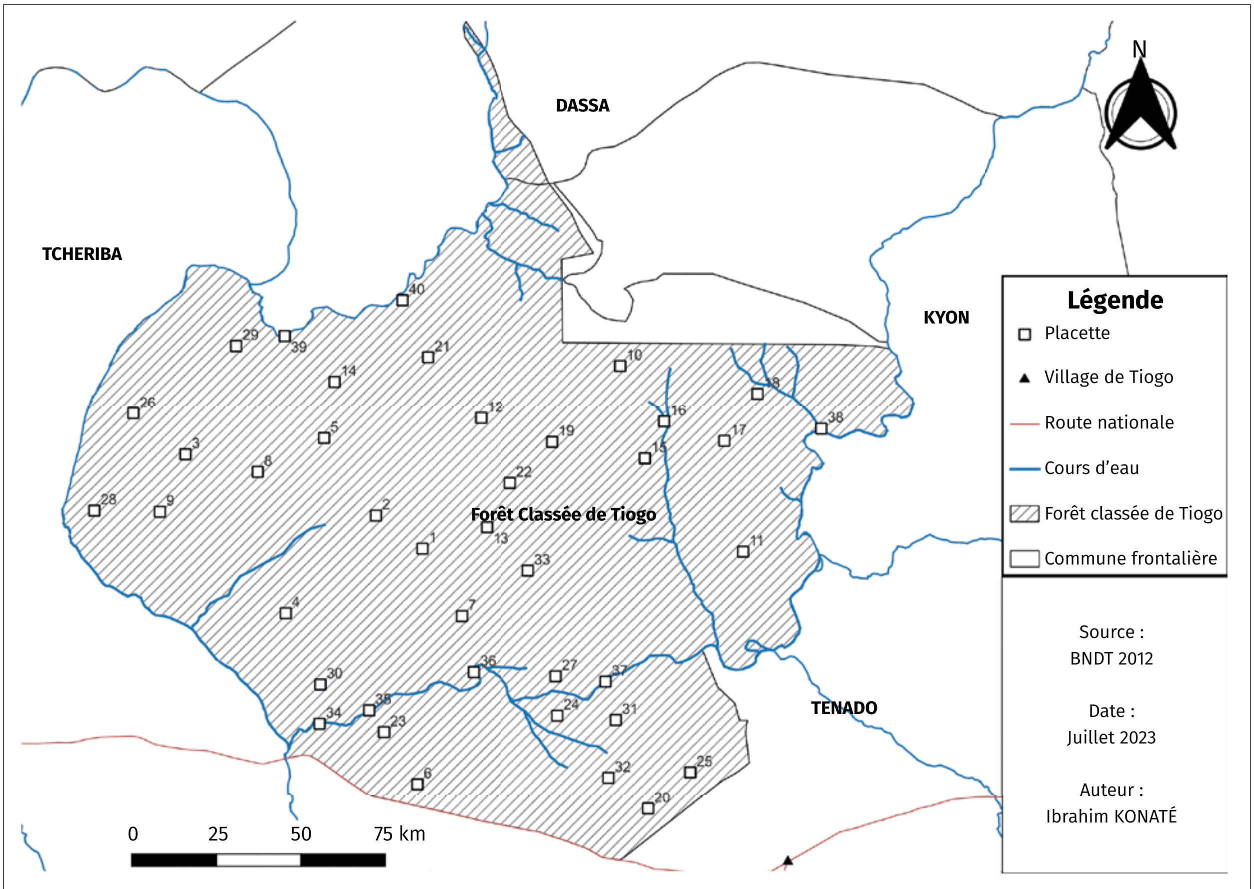


Figure 4.
Répartition des placettes d'inventaire forestier à l'échelle de la Forêt Classée de Tiogo, Burkina Faso.
Distribution of forest inventory plots throughout the Tiogo Forest Reserve, Burkina Faso.

Tableau II.
Répartition des placettes d'inventaire forestier dans chacune des unités d'occupation de terre dans la Forêt Classée de Tiogo, Burkina Faso.
Distribution of forest inventory plots in each of the land-use units in the Tiogo forest reserve, Burkina Faso.

Unité d'occupation des terres	Superficie (ha)	Nombre de placettes
Savane arbustive	8 158	11
Cultures pluviales et territoires agroforestiers	7 635	7
Savane arborée	11 448	15
Forêt galerie	472	7
Total	**27 713**	**40**

Source : données terrain, 2021.

Calcul du taux de réponse

Le taux de réponses fournies par les enquêtés suivant le type de facteurs (cause de dégradation, rapport avec la forêt, besoins énergétiques) a été calculé en utilisant la formule :

$$F = \frac{S}{N} \times 100 , \qquad \text{(équation 5)}$$

avec F : taux de réponse pour le type d'utilisation (%) ; S : nombre de personnes ayant fourni une même réponse par rapport à un facteur donné ; N : nombre total de personnes interviewées.

Consentement des enquêtés

Avant le début de chaque entrevue, les agents de terrain qui conduisaient les enquêtes ont explicitement souligné la nature académique de l'enquête et la manière anonyme dont les réponses seraient traitées. Avec ces informations, tous les participants aux enquêtes ont librement donné leur consentement pour répondre aux questions.

Évaluation de la diversité floristique et quantification du carbone aérien

Cette étape à travers un inventaire forestier évalue l'implication des changements d'unités d'occupation des terres, en termes de diversité ligneuse et de stock de carbone aérien.

Plan de sondage

Un échantillonnage aléatoire stratifié disproportionné a été appliqué. Quarante placettes de 50 × 50 m (2 500 m²) ont été inventoriées et réparties (figure 4) dans les différentes unités d'occupation de terres (tableau II). La taille de placette dans cette étude (2 500 m²) s'inspire de la taille des placettes des dispositifs expérimentaux installés depuis 1992 dans les Forêts Classées de Tiogo et de Laba au Burkina Faso (Sawadogo, 2009) et aussi des tailles de placettes utilisées par certains auteurs dans des formations similaires (Dayamba *et al.,* 2016 ; Ky-Dembele *et al.,* 2019). Le nombre de placettes par unité d'occupation des terres a tenu compte de leur hétérogénéité.

Inventaire floristique

Dans chaque placette, le nom scientifique des espèces rencontrées ainsi que les données dendrométriques sont relevés. Il s'agit de :
- la circonférence à hauteur de poitrine à 1,30 m au-dessus du sol ($C_{1,30\ m}$), mesurée à l'aide d'un ruban de couturier. Elle a été ensuite convertie en diamètre à hauteur de poitrine (*Diameter at breath height*, DBH) par la relation :

$$DBH = \frac{C_{1,30\,m}}{\pi} \qquad \text{(équation 6)}$$

avec $C_{1,30\ m}$ le diamètre à 1,30 m seulement pour les individus de hauteur supérieure à 10 cm au-dessus du sol (Sawadogo, 2009 ; Dayamba *et al.,* 2016).
- la hauteur totale a été mesurée à l'aide d'une perche graduée de 7 m ou d'un clinomètre (SUUNTO) pour les sujets dont la hauteur est supérieure à 7 m. Pour les individus multicaules, la hauteur et la circonférence de la tige la plus haute ont été mesurées.

Calcul de la richesse et de la diversité floristique ligneuse

La richesse spécifique représente le nombre total d'espèces présentes par unité d'occupation des terres.

La diversité a été déterminée par l'indice de diversité de Shannon (H') dont la formule est :

$$H' = -\sum_{i=1}^{S} pi \ln pi \qquad \text{(équation 7)}$$

avec S = richesse spécifique ; pi = abondance relative ($pi = n_i / N$ avec n_i = nombre d'individus d'une espèce i et N = nombre total d'individus dans la parcelle) ; ln = logarithme népérien.

Il est généralement utilisé par des auteurs et est exprimé en bits dont les valeurs extrêmes sont comprises entre 0,5 (faible) et 4,5 bits environ (grande) (Tindano *et al.*, 2021 ; Kumar *et al.*, 2022).

Quantification de la biomasse et du stock de carbone aérien

Les données d'inventaire ont servi aussi à estimer la biomasse aérienne ligneuse (AGB) et le stock de carbone correspondant. Nous avons utilisé l'équation généralisée pantropicale de Chave *et al.* (2014) :

$$AGB = 0{,}0673 \times (\rho D^2 H)^{0{,}976} \qquad \text{(équation 8)}$$

avec ρ = densité spécifique du bois ; D (cm) = diamètre à 1,30 m du sol ; H (m) = hauteur totale et AGB = biomasse aérienne ligneuse.

Cette équation est proposée pour les forêts sèches. Elle a été préférée aux équations spécifiques qui n'étaient pas disponibles pour toutes les espèces rencontrées lors des inventaires. Le stock de carbone aérien a été calculé en multipliant AGB par 0,5 qui est la fraction carbone donnée par le GIEC (2003).

Analyse des données

Analyse de la dynamique du couvert végétal

La dynamique du couvert végétal a été appréciée à partir du calcul du taux de changement des unités d'occupation des terres. Ces informations ont permis d'évaluer leur évolution en termes de superficie. De même, la détermination de la matrice de transition donne un aperçu sur l'évolution temporelle du couvert végétal. Ces aspects ont été décrits en détail ci-dessus.

Analyse statistique des données d'enquêtes

Les calculs des taux de réponse ont servi à générer des histogrammes de fréquences de réponse par rapport à la perception des facteurs de dégradations (directs ou secondaires) et aux propositions de gestion. Par ailleurs, un test de Khi2 (χ^2) a été réalisé pour tester l'hypothèse d'indépendance entre les profils des enquêtés (variable indépendante) et les facteurs de dégradation (variable dépendante).

Au préalable, il a été vérifié que toutes les fréquences absolues étaient supérieures à 5, ce qui confirme la condition de validité de ce test (Sambiéni *et al.*, 2015).

Analyse statistique des données sur la végétation ligneuse

Au préalable, le test de Shapiro-Wilk a été réalisé pour tester la normalité des distributions des données. Une analyse de variance à un facteur a été effectuée pour tester s'il y avait un effet significatif des unités d'occupation des terres sur le stock moyen de carbone aérien à l'hectare. Pour la diversité (H), comme le test de Shapiro-Wilk n'a pas validé la normalité de la distribution, nous avons utilisé le test non-paramétrique de Kruskal-Wallis pour tester s'il y avait un effet significatif des unités d'occupation des terres sur la diversité (H).

Nous avons aussi réalisé des analyses de courbes d'accumulation pour estimer la variation de la richesse des espèces en fonction de l'effort d'échantillonnage.

Ensuite, en supposant que le stock moyen de carbone aérien à l'hectare ne varie pas au cours du temps dans chaque unité d'occupation des terres, nous avons utilisé le stock de carbone aérien (à l'hectare) pour chaque unité d'occupation des terres et la superficie du type d'unité d'occupation des terres à différentes dates (correspondant aux dates des images analysées ; 1990, 1999, 2009 et 2019) pour tracer des courbes qui montrent la fluctuation de ce stock carbone aérien dans chaque unité d'occupation des terres ainsi que dans toute la FCT sur les 30 ans.

Les analyses statistiques ont été réalisées avec le logiciel libre R version 4.3.3.

Résultats

Changements d'occupation des terres

Dynamique spatio-temporelle de la végétation

Les cartes d'occupation des terres de la FCT en 1990, 1999, 2009 et 2019 sont présentées dans les figures 5A et 5B. Elles montrent que la superficie des cultures pluviales et territoires agroforestiers et de la savane arbustive a augmenté entre 1990 et 2019 au détriment de la savane arborée.

Les précisions globales des classifications varient entre 72 % et 93 % et les indices de Kappa entre 0,69 et 0,92 (tableau III).

Évolution temporelle de l'occupation des terres

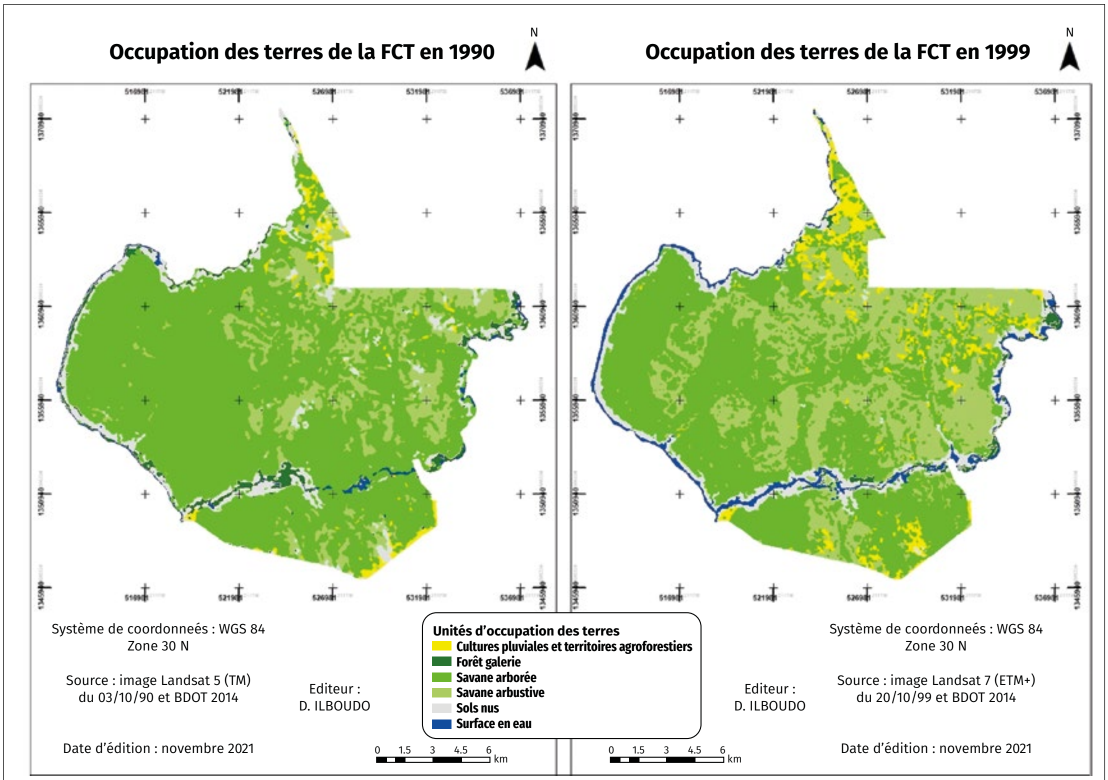
La matrice de transition ou de conversion par unité d'occupation des terres entre 1990 et 2019 est présentée dans le tableau IV.

Sur les trois décennies, le tableau IV montre que sur une superficie de savane arborée de 21 593 ha en 1990, 5 089 ha se sont transformés en cultures pluviales et territoires agroforestiers et 5 266 ha en savane arbustive ; soit une perte de 47 % de savane arborée entre 1990 et 2019 au profit des cultures pluviales et territoires agroforestiers et de la savane arbustive.

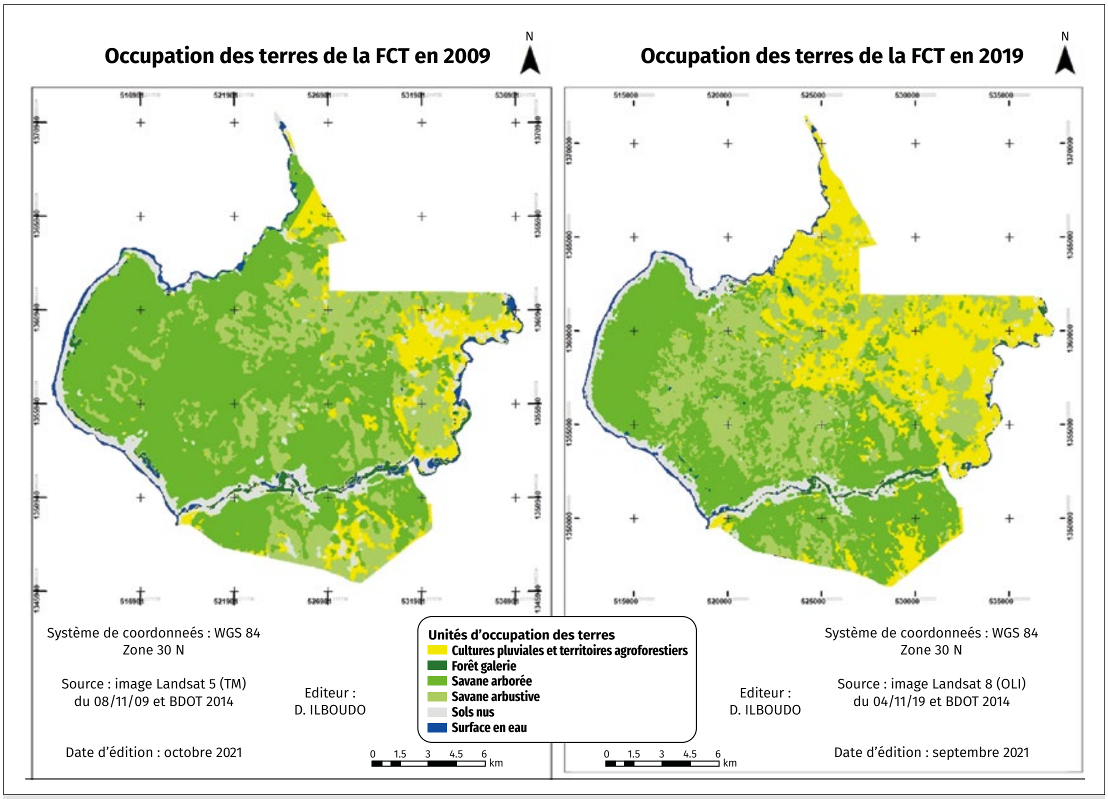
Sur la période de 1990 à 1999, la superficie des cultures pluviales et territoires agroforestiers et des savanes arbustives ont augmenté avec un gain moyen annuel respectivement de 20 % et de 11 % (annexe 3). Ces augmentations se sont faites au détriment des savanes arborées qui ont connu une perte annuelle de 3 %. Une tendance régressive de la forêt galerie a également été observée sur la même période avec un taux moyen annuel de 6 %.

Tableau III.
Indices d'évaluation de la qualité des images classifiées.
Indices for assessing the quality of classified images.

	Année de production de l'image			
Paramètres	**1990**	**1999**	**2009**	**2019**
Précision globale (%)	72	90	93	89
Indice de Kappa	0,69	0,89	0,92	0,89



Figures 5A.
Changements d'occupation des terres dans la Forêt Classée de Tiogo de 1990 et 1999, Burkina Faso.
Changes in land use in the Tiogo Forest Reserve between 1990 and 1999, Burkina Faso.



Figures 5B.
Changements d'occupation des terres dans la Forêt Classée de Tiogo de 2009 et 2019, Burkina Faso.
Changes in land use in the Tiogo Forest Reserve between 2009 and 2019, Burkina Faso.

Tableau IV.
Matrice de transition des unités d'occupation des terres entre 1990 et 2019. Les valeurs du tableau représentent des superficies (unité : ha). Les valeurs en gras dans les cellules de la diagonale indiquent la stabilité de la superficie des unités entre 1990 et 2019.
Transition matrix of land use units between 1990 and 2019. The values in the table represent areas (unit: ha). The bold values in the diagonal cells indicate the stability of the area of the units between 1990 and 2019.

Type d'occupation des terres en 1990	Type d'occupation des terres en 2019						
	Cultures pluviales et territoires agroforestiers	Forêt galerie	Savane arborée	Savane arbustive	Sols nus	Surface en eau	Superficie totale (ha) en 1990
Cultures pluviales et territoires agroforestiers	**510**	1	49	37	19	1	617
Forêt galerie	212	**192**	53	18	283	168	928
Savane arborée	5 089	215	**10 475**	5 266	457	91	21 593
Savane arbustive	1 193	0	786	**2 647**	25	0	4 652
Sols nus	613	23	74	186	**812**	54	1 761
Surface en eau	17	42	10	3	89	**150**	311
Superficie totale (ha) en 2019	7 635	472	11 448	8 158	1 685	464	**29 862**

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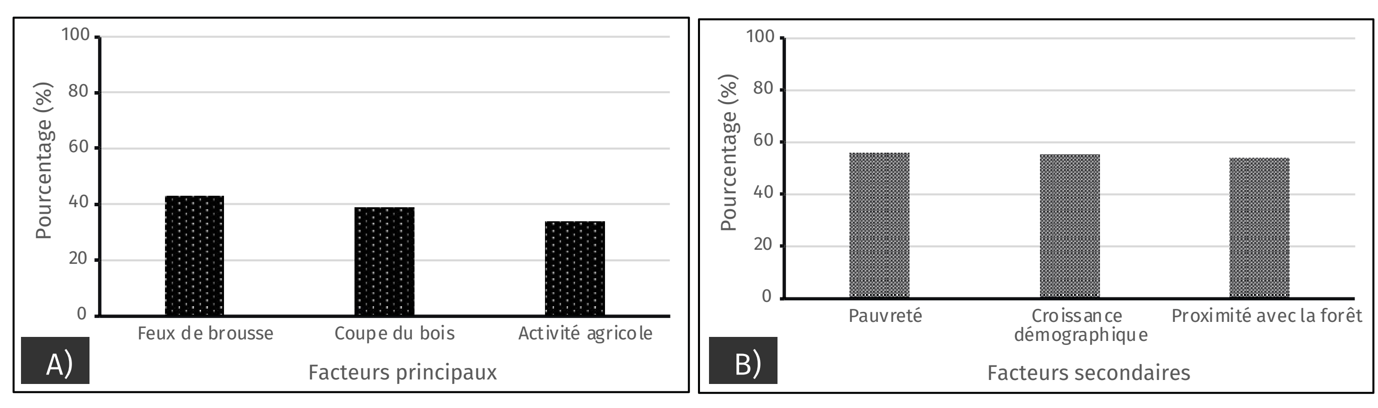
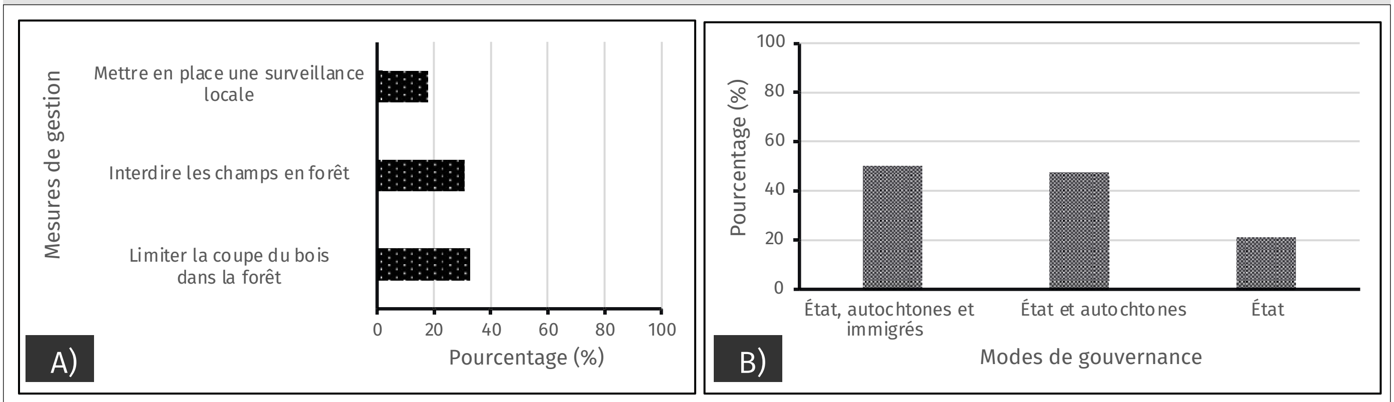


Figures 6.
Perception des enquêtés sur les facteurs principaux (directs) (A) et secondaires (jacents) (B) de la déforestation et de la dégradation de la Forêt Classée de Tiogo, Burkina Faso.
Respondents' perceptions of the main (direct) factors (A) and secondary (underlying) factors (B) in deforestation and degradation of the Tiogo Forest Reserve, Burkina Faso.



Figures 7.
Perceptions des enquêtés sur les règles de gestion (A) et le mode de gouvernance (B) qui seraient adéquat pour la Forêt Classée de Tiogo, Burkina Faso.
Respondents' perceptions of the management rules (A) and mode of governance (B) that would be appropriate for the Tiogo Forest Reserve, Burkina Faso.

La hausse de la superficie des cultures pluviales et territoires agroforestiers a été également enregistrée sur la période de 1999 à 2009 (annexe 4). En effet, le taux moyen annuel de cette hausse s'établit à 7 % et traduit la conversion de la superficie forestière (savane arborée 0,82 % et forêt galerie 3 %) en surface agricole. De même, on a observé un accroissement de la superficie des savanes arbustives dont la moyenne annuelle de changement est de 2 %. Par contre, une régression de la savane arborée dont la perte moyenne annuelle est de 0,25 % a été enregistrée.

Sur la période de 2009 à 2019, l'activité agricole s'est intensifiée dans la FCT, entraînant une augmentation de la superficie des cultures pluviales et des territoires agroforestiers (annexe 5). Cela se traduit par un accroissement moyen de ces superficies de l'ordre de 17 %. De même, l'expansion des terres agricoles a provoqué une régression des superficies des savanes arborées et des forêts galeries, tandis que les savanes arbustives ont connu un gain. Les taux de changement de ces terres sur l'ensemble des unités d'occupation sont respectivement de 3 %, 1 % et 3 % pour la savane arborée, la savane arbustive et la forêt galerie.

Moteurs des changements du couvert végétal et modes de gestion

Changements observés et facteurs de conversion

• ***Profil des personnes enquêtées***

Les personnes enquêtées étaient composées de 81 % d'hommes et 19 % de femmes et 96 % d'entre eux étaient mariés. Environ 66 % des enquêtés n'ont eu accès à aucun système éducatif, 7 % ont suivi des cours d'alphabétisation en langues locales contre 6 % pour ceux qui ont fréquenté l'école rurale. Par ailleurs, 13 % ont déclaré avoir le niveau primaire. Quant au niveau secondaire, la proportion est de l'ordre de 7 %.

Les populations enquêtées tirent leurs revenus principalement de l'agriculture (94 %) et de l'élevage (3 %). Les autres secteurs d'activités comme les exploitants forestiers, les commerçants et d'autres activités telles que la pêche, l'orpaillage et l'artisanat sont faiblement représentés avec des proportions respectives de 0,33 %, 2 % et 2 %. Concernant les activités secondaires, les données ont montré que les activités de maraîchage occupent 44 % de la population enquêtée. Les éleveurs représentent 17 %, les exploitants forestiers (débiteurs) sont évalués à 8 % et les commerçants à 8 %. Les autres activités (agriculture, orpaillage, mécanique moto, etc.) représentent 15 %. Les personnes qui n'exercent aucune activité secondaire représentent 15 % des enquêtés.

• *Facteurs de dégradation*

Les personnes enquêtées ont observé des changements dans la FCT ces 30 dernières années. Ils ont, en effet, relevé une réduction de la densité et de la diversité de la végétation à travers la réduction des espèces pourvoyeuses de produits forestiers non-ligneux (PFLN). La déforestation a été également citée comme un changement majeur, de même que l'accroissement du nombre et de la superficie de cultures pluviales et territoires agroforestiers. Les raisons principales et secondaires de la dégradation sont données dans les figures 6. La figure 6A montre que les feux de brousse (photo 5), la coupe du bois (photo 6) et l'activité agricole (photo 4) constituent les trois principales raisons de la dégradation de la forêt avec respectivement 43 %, 39 % et 34 %. Au niveau des raisons secondaires, il s'agit de la pauvreté (56 %), suivie de la croissance démographique (55,4 %) et de la proximité avec la forêt (54 %) (figure 6B).

L'analyse des données d'enquête montre que le niveau d'instruction (p-value = 0,007) et la distance avec la forêt (p-value = 0,006) ont une influence significative sur la perception en lien avec les facteurs directs de dégradation. Les plus instruits qui constituent la minorité sont conscients que la dégradation de la forêt est liée essentiellement aux feux de brousse incontrôlés, à la coupe anarchique du bois et à l'extension des cultures pluviales et territoires agroforestiers. Pour les raisons secondaires de dégradation, seule la distance est une variable déterminante (p-value = 0,009). En effet, les populations les plus proches de la FCT sont celles qui exploitent le plus la forêt à travers la coupe du bois et l'installation des cultures pluviales et territoires agroforestiers.

• *Propositions de mode de gestion et de gouvernance par les enquêtés*

Pour remédier à la dégradation de la forêt et préserver son potentiel pourvoyeur de services écosystémiques, les enquêtés ont proposé des actions à entreprendre et un mode de gouvernance à mettre en place (figures 7).

Les résultats font ressortir comme mesures de gestion proposées par les enquêtés, dans leur majorité, le besoin de limiter la coupe de bois et d'appliquer la mesure d'interdiction des cultures pluviales et territoires agroforestiers en forêt (figure 7A). En outre, comme mode de gouvernance, la majorité propose que l'État, en collaboration

Photo 5.
Feux de brousse dans la Forêt Classée de Tiogo, Burkina Faso.
Bush fires in the Tiogo Forest Reserve, Burkina Faso.
Photo S. D. Dayamba.

Photo 6.
Coupe anarchique du bois dans la Forêt Classée de Tiogo, Burkina Faso.
Illegal logging in the the Tiogo Forest Reserve, Burkina Faso.
Photo I. Konaté.

avec les populations riveraines, s'engage à faire respecter les modes de gestion (figure 7B). Dans l'ensemble, certaines mesures de gestion proposées sont déjà des dispositions du code forestier et cela sous-entend une méconnaissance de la réglementation forestière.

Tableau V.
Richesse spécifique, nombre d'individus et indice de Shannon (H) moyen par type d'occupation des terres. Pour la diversité (H), les unités d'occupation des terres avec des lettres différentes ont des moyennes significativement différentes ; le test de Kruskal-Wallis avec un risque de 5 % a été utilisé pour établir les différences statistiques entre les unités d'occupation des terres.
Average species richness, number of individuals and Shannon index (H) by land cover type. For diversity (H), land-use units with different letters have significantly different means; the Kruskal-Wallis test with a 5% risk was used to establish statistical differences between land-use units.

Type d'occupation	Richesse spécifique	Nombre d'individus	Shannon (H)
Cultures pluviales et territoires agroforestiers	24	82	1,31 ± 0,62a
Forêt galerie	17	475	0,63 ± 0,41a
Savane arborée	51	1 588	2,14 ± 0,31b
Savane arbustive	43	464	1,92 ± 0,43b

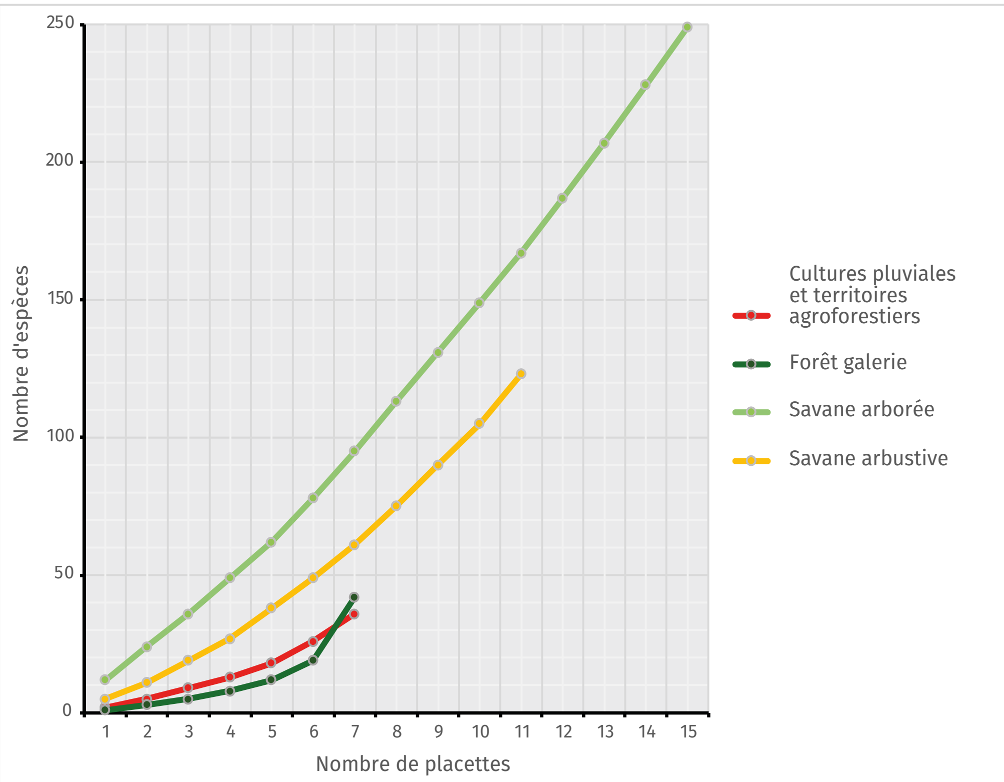


Figure 8.
Accumulation de la richesse spécifique en fonction du nombre de placettes par type d'occupation du sol dans la Forêt Classée de Tiogo, Burkina Faso.
Accumulation of species richness as a function of the number of plots per land-use type in the Tiogo Forest Reserve, Burkina Faso.

Diversité floristique et stock de carbone aérien

Richesse et diversité de la végétation ligneuse

Les individus mesurés dans l'ensemble des unités d'occupation des terres comptaient 68 espèces ligneuses. Le plus grand nombre d'espèces a été recensé dans les savanes arborées (51 espèces dont 35 genres et 18 familles) et dans les savanes arbustives (43 espèces dont 30 genres et 13 familles). Les cultures pluviales et territoires agroforestiers et les forêts galeries avaient respectivement 24 espèces - dont 20 genres et 12 familles et 17 espèces - dont 15 genres et 12 familles.

L'analyse de la diversité (H) a montré une différence significative (p-value = 0,0001) entre les deux types de savane et les autres occupations des terres (forêt galerie et cultures pluviales et territoires agroforestiers). En effet, les diversités de la savane arborée (2,14 ± 0,31) et de la savane arbustive (1,92 ± 0,43) étaient plus importantes que celles des cultures pluviales et territoires agroforestiers (1,31 ± 0,62) et de la forêt galerie (0,63 ± 0,41) (tableau V).

Il a été montré que les pentes des courbes d'accumulation des espèces ont tendance à être plus fortes pour les deux types de savane que pour les cultures pluviales et territoires agroforestiers et la forêt galerie (figure 8). Aucune des 4 courbes ne converge vers une asymptote.

Stock de carbone aérien

La forêt galerie stocke 35,47 ± 21,35 tC/ha et constitue le plus important réservoir de carbone de la FCT en comparaison aux formations de savane et des zones cultivées. Les cultures pluviales et territoires agroforestiers ont le plus faible stock de carbone aérien (tableau VI). La savane arborée stocke 7,06 ± 1,70 tC/ha contre 2,48 ± 0,6 tC/ha au niveau de la savane arbustive.

Tenant compte du stock de carbone estimé à l'hectare dans chaque unité d'occupation des terres et du changement d'occupation des terres, la figure 9 montre les évolutions de stock de carbone dans les différentes unités de la forêt ainsi que le total (sur toute la superficie de la forêt). Dans cette figure, on remarque que la courbe du carbone total a la même tendance que celles du stock de carbone aérien de la savane arborée et de la forêt galerie. En effet, ces courbes montrent une forte régression du stock de carbone aérien de 1990 à 1999, puis une légère augmentation en 2009 et une forte baisse entre 2009 et 2019. Au niveau de la savane arbustive, le stock de carbone aérien a augmenté de 1990 à 1999 puis n'a pratiquement pas évolué jusqu'en 2019. Concernant les cultures pluviales et territoires agroforestiers, le stock de carbone très faible de 1990 à 2009 a remarquablement augmenté entre 2009 et 2019. En 30 ans le stock de carbone aérien a considérablement baissé de façon générale, et particulièrement dans la savane arborée et dans la forêt galerie. Globalement, la FCT a perdu 41 % de carbone aérien entre 1990 et 2019 comme conséquence des changements des unités d'occupation des terres.

Discussion

Dynamique de la couverture végétale

L'analyse de la dynamique spatiale sur la période de 1990 à 2019 a montré une régression des formations boisées, notamment les savanes arborées et la forêt galerie, et un accroissement des superficies des savanes arbustives et des cultures pluviales et territoires agroforestiers qui sont relativement pauvres en ligneux. Cela témoigne d'une déforestation et d'une dégradation de la FCT. Le même constat a été fait par d'autres auteurs au Burkina Faso (Soulama *et al.*, 2015 à la réserve partielle de faune de Pama et de ses périphéries de 2001 à 2013 ; Gansaonré *et al.*, 2020 à la périphérie du Parc national W, parc transfrontalier partagé entre le Bénin, le Burkina Faso et le Niger, de 1984 à 2015) et au Mali (Daou *et al.*, 2019 en zone soudano-sahélienne dans la commune rurale de Nyamina de 1985 à 2018). En outre, dans la zone soudanienne au Nord-est du Bénin, les travaux de Zakari *et al.* (2018) ont également montré une forte savanisation de la forêt classée des trois rivières qui se traduit par une déforestation et une dégradation des superficies des forêts galeries, des forêts denses sèches et des forêts claires et une extension des mosaïques de cultures, des jachères et des savanes arborées et arbustives entre 1995 et 2013. Cette tendance de dégradation a également été rapportée par Dimobe *et al.* (2017) dans le ranch de gibier de Nazinga entre 1984 et 2013, qui serait due aux actions anthropiques telles que la coupe du bois, les feux de brousse, les cultures pluviales et territoires agroforestiers et le surpâturage. Par ailleurs, au cours de nos enquêtes, 19 % des personnes ont déclaré disposer de champs (assimilés aux cultures pluviales et territoires agroforestiers) dans les limites de la forêt. Ces enquêtes ont également montré que 90 % des personnes interrogées ont recours au bois comme seule source d'énergie, lequel bois proviendrait de la FCT. Toutefois, comparé à la période 1990-1999, le rythme de progression des cultures pluviales et territoires agroforestiers et savane arbustive pour la période 1999-2009 a diminué, passant respectivement de 20 à 7 % et de 11 à 2 %. En outre, entre ces mêmes périodes,

Tableau VI.
Stock de carbone ligneux par unité d'occupation des terres.
Woody carbon stock per unit of land use.

	Unités d'occupation des terres				
	Savane arborée	Savane arbustive	Forêt galerie	Cultures pluviales et territoires agroforestiers	p-value
Carbone aérien ligneux (tC/ha)	7,06 ± 1,70	2,48 ± 0,60	35,47 ± 21,35	1,72 ± 0,68	< 0,001

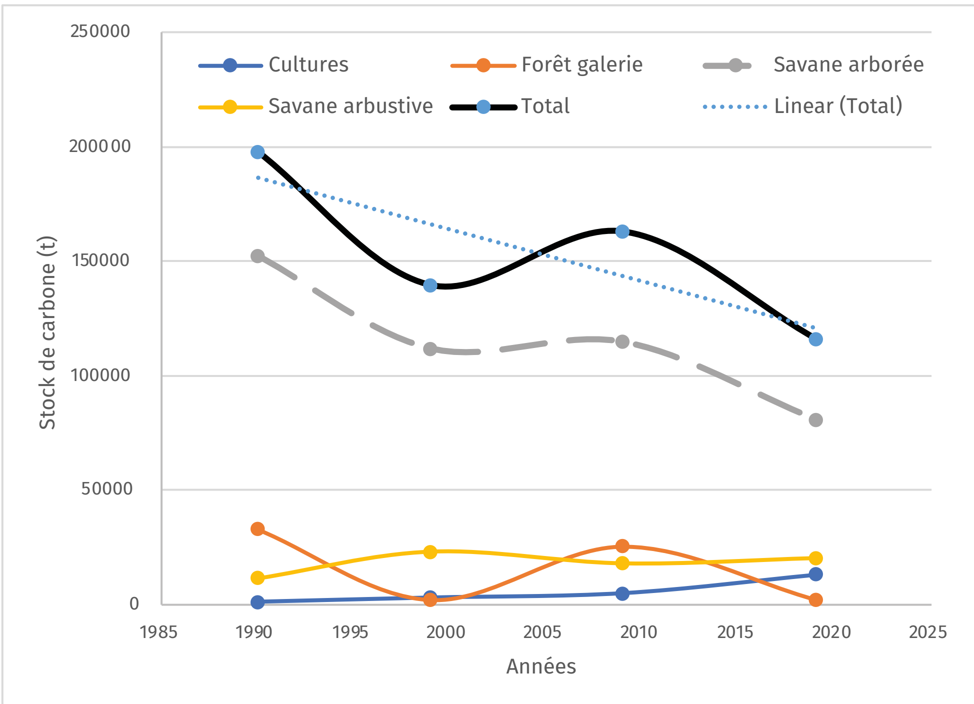


Figure 9.
Évolution du stock de carbone sur les superficies des unités de la Forêt Classée de Tiogo, Burkina Faso. C.P T. A : cultures pluviales et territoires agroforestiers.
Evolution of carbon stock in the areas of the Tiogo classified forest units, Burkina Faso. C.P T. A: rainfed crops and agroforestry areas.

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la perte annuelle de l'aire de la savane arborée a baissé de 3 à 0,25 %. Ces résultats montrent qu'entre ces périodes, les zones boisées auraient subi moins de pressions anthropiques et cela serait dû aux interventions de structures techniques. En effet, l'Institut de l'Environnement et de Recherches Agricoles (INERA) du Burkina Faso en collaboration avec l'Université Suédoise des Sciences Agricoles (SLU) et l'Agence Suédoise de Coopération Internationale pour le Développement (ASDI) avait financé plusieurs thèses doctorales (Savadogo, 2007 ; Zida, 2007 ; Traoré, 2008 ; Sawadogo, 2009 ; Dayamba, 2010) sur l'écologie de la végétation dans cette forêt qui était alors fréquentée en permanence pour la mise en place des essais et la collecte des données. Ceci du même coup constituait une surveillance et une protection pour la forêt. Mais après les années 2009, l'intensité des activités a diminué à cause de la fin des projets et la pression par les communautés riveraines s'était encore intensifiée, menant à un accroissement du rythme de progression des cultures pluviales et territoires agroforestiers et savanes arbustive sur la période 2009-2019. Un constat similaire a été fait par Gansaonré *et al.* (2020) dans la zone périphérique du Parc W qui avaient trouvé une augmentation des superficies de la savane boisée et arborée au détriment de la savane arbustive entre 1999 et 2015. Selon ces auteurs, cela pourrait s'expliquer par l'intervention des projets de préservation, des acteurs communaux et des structures techniques de l'État qui avaient mis en œuvre des actions d'aménagement.

Les feux de brousse, la pratique de l'activité agricole, la coupe du bois constituent les trois principaux facteurs de la déforestation et de la dégradation de la FCT selon les enquêtes. Ces résultats corroborent ceux d'autres auteurs (Dimobe *et al.,* 2017 ; Zakari *et al.,* 2018 ; Brun *et al.,* 2020) qui ont constaté que l'agriculture et l'exploitation forestière sont les principales causes de régression du couvert végétal dans des écosystèmes similaires au nôtre. Le feu est considéré comme le premier facteur de dégradation par nos enquêtés du fait de son impact très dévastateur sur le couvert végétal. Les enquêtés estiment qu'à l'issue des opérations de défriche et d'installation de cultures pluviales et territoires agroforestiers, l'exploitation agricole peut se faire dans les mêmes limites pendant plusieurs années (sans s'étendre), contrairement aux feux qui se propagent rapidement et chaque année, pouvant brûler sur de nouvelles superficies. Concernant la coupe du bois, les insuffisances dans le fonctionnement du Chantier d'aménagement forestier (CAF) sont responsables de la coupe anarchique de bois (surtout le bois vert) dans la forêt. L'insuffisance dans la surveillance du massif forestier par le personnel forestier a renforcé cet état de fait. Il ressort de nos enquêtes et de nos observations sur le terrain qu'entre 120 et 160 m^3 de bois transportés dans des tricycles sortent de la forêt au quotidien. Le phénomène de la coupe du bois s'est accentué de 2009 à nos jours, avec notamment le bitumage de la route avoisinant la FCT (route Koudougou-Dédougou) en 2012 rendant plus facile l'acheminement du bois vers les grands centres urbains.

L'analyse des résultats d'enquêtes montre aussi que la proximité à la forêt est un facteur indirect significatif pour la dégradation de la forêt. D'autres facteurs comme la pauvreté et la croissance démographique ont aussi été rapportés. Ces résultats sont similaires aux travaux de Kambire *et al.* (2015) au Burkina Faso, d'Ahononga *et al.* (2020) et de Brun *et al.* (2020) au Bénin. Les mêmes observations ont été faites par Jiagho *et al.* (2021) indiquant que les facteurs secondaires de la dégradation du Parc National de Waza et sa périphérie au Cameroun sont liés à la croissance démographique et aux facteurs économiques. La combinaison des facteurs « pauvreté et croissance démographique » conduit à une surexploitation des ressources naturelles forestières par les communautés riveraines pour des besoins de subsistance. Cette situation est beaucoup plus perceptible dans les communautés installées à proximité de la FCT qui y pratiquent la coupe du bois, les activités de production agricole et le pâturage. C'est le cas au niveau des villages de Ziliwélé, Négarpoulou et Essapoun. Les causes secondaires de la dégradation des ressources forestières identifiées dans cette étude permettent de dire qu'en intensifiant la sensibilisation et en créant les conditions pour que les communautés aient accès à des moyens de subsistance alternatifs, on pourrait contribuer substantiellement à la préservation de la forêt.

Diversité floristique de la végétation

Nous avons trouvé que la diversité floristique (H') des deux types de savane était plus importante que celles de la forêt galerie et des cultures pluviales et territoires agroforestiers. Nos valeurs moyennes obtenues (2,14 et 1,92) pour la savane arborée et la savane arbustive sont similaires à celles trouvées par Tiendrébeogo *et al.* (2022) dans la Forêt Classée de Péni au Sud-ouest du Burkina Faso sur ces 2 unités d'occupation des terres (2,06 et 1,94). La faible diversité floristique dans la forêt galerie serait liée aux conditions édaphiques (humides et argileuses) qui la rendent appropriée à seulement quelques espèces comme *Mitragyna inermis* (Willd.) K.Schum. Ces conditions sont, en effet, asphyxiantes et très sélectives pour l'implantation et l'épanouissement de plusieurs espèces (Ouédraogo *et al.*, 2008). Dans les cultures pluviales et territoires agroforestiers, la diversité ligneuse est relativement faible et on observe une dominance des arbres dits utilitaires, notamment les pourvoyeurs de produits forestiers non-ligneux (PFLN) comme *Vitellaria paradoxa* C.F.Gaertn., *Parkia biglobosa* (Jacq.) R.Br. ex G.Don et *Lannea microcarpa* Engl. & K.Krause. Comme l'ont relevé Soulama *et al.* (2015), malgré la préservation des arbres utiles dans les cultures pluviales et territoires agroforestiers, la destruction totale des autres arbres afin de limiter l'effet de l'ombre et la compétition entre les cultures et les ligneux ne favorise pas la reconstitution de la végétation originelle.

Cependant, comme aucune courbe d'accumulation de la richesse des espèces ne converge vers un plateau, cette étude révèle que l'échantillonnage prévu n'a pas été suffisant pour estimer correctement la richesse floristique au sein de chaque unité d'occupation des terres. De plus, comme l'effort d'échantillonnage a été moindre pour la forêt galerie et les cultures pluviales et territoires agroforestiers, cela suggère que nous avons certainement sous-estimé leur diversité. Par conséquent, des échantillonnages additionnels, voire l'analyse de parcelles de dimensions accrues, seraient nécessaires pour mieux estimer la biodiversité de chaque unité.

Stock de carbone aérien

L'analyse du stock de carbone aérien montre que la forêt galerie enregistre les valeurs les plus élevées par rapport aux autres unités d'occupation des terres. Cela pourrait se justifier par la dominance des sujets de gros diamètres sur cette unité par rapport aux autres unités d'occupation de terres de la forêt classée. En effet, 53 % des ligneux dans cette formation ont un DBH ≥ 10 cm contre 12,6 % pour ceux dont le DBH ≥ 40 cm, alors que pour la savane arborée par exemple, ces pourcentages sont respectivement de 30 % et de 0,4 %. Ces résultats corroborent les travaux de Qasim *et al.* (2016) et de Monssou *et al.* (2016). Par ailleurs, la densité ligneuse qui est fonction du type d'unité d'occupation des terres détermine aussi le potentiel de stock de carbone aérien, comme indiqué par les travaux conduits dans les provinces du Ziro et des Balé au Burkina Faso par Dayamba *et al.* (2016). En effet, la valeur du stock de carbone aérien plus importante dans la forêt galerie serait aussi liée à sa densité arborée plus élevée (271 tiges/ha) par rapport aux autres unités d'occupation des terres.

L'étude a aussi révélé une perte de stock de carbone de 41 % entre 1990 et 2019 comme conséquence des changements d'unités d'occupation des terres dans la FCT. Ceci traduit toute l'urgence d'actions concrètes qui fourniraient aux communautés riveraines des moyens alternatifs de subsistance pour préserver les ressources forestières.

Conclusion

Cette étude, conduite en zone de savane soudanienne en Afrique de l'Ouest, a évalué la dynamique de la couverture végétale de la forêt classé de Tiogo sur une période de 30 ans, les moteurs des changements et les implications pour la diversité ligneuse et le stock de carbone aérien de la strate ligneuse de la Forêt Classée de Tiogo. Les résultats ont montré que sur une superficie de savane arborée de 21 593 ha en 1990, 5089 ha se sont transformés en cultures pluviales et territoires agroforestiers et 5 266 ha en savane arbustive en 2019 ; soit une perte de 47 % de savane arborée au profit d'unités moins boisées. Les feux de brousse, la coupe du bois et l'activité agricole constituent les facteurs directs de cette dégradation, tandis que la pauvreté, la croissance démographique et la proximité des populations avec la forêt sont les causes secondaires. Concernant le stock de carbone aérien, la forêt galerie et la savane arborée présentent les plus importants réservoirs de carbone comparativement à la savane arbustive et aux cultures pluviales et territoires agroforestiers. Les changements des unités d'occupation des terres dans la FCT marqués par 47 % de perte du couvert de la savane arborée, couplés au potentiel de séquestration de carbone de chaque unité d'occupation des terres, ont induit pour la FCT une perte de 81 901 tonnes de carbone entre 1990 et 2019, soit une réduction de 41 % du potentiel de la forêt. Ces résultats confirment nos hypothèses qui stipulent que le statut classé de cette forêt n'a pas suffi à la protéger des actions anthropiques et que les mêmes tendances de dégradation de végétation dans les zones non protégées ou classées y avaient cours, avec des implications de perte substantielle de carbone. Pour préserver la FCT, l'étude recommande (1) d'intensifier les sensibilisations à l'endroit des populations, (2) de trouver les voies et moyens pour promouvoir des moyens de subsistance alternatifs pour les riverains, (3) de promouvoir des sources alternatives d'énergie pour les ménages ruraux et urbains et (4) de prendre en compte les propositions faites par les communautés environnantes de la FCT pour permettre de faire assoir un mode de gouvernance qui préserve au mieux la forêt.

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Cette étude s'inscrit dans le cadre d'un projet de recherche sur « la quantification du stock de carbone, le calibrage des modèles de quantification de carbone séquestré et le suivi de la dynamique du stock de carbone en zone de savane au Burkina Faso », financé par le CILSS à travers le projet régional « GCCA+ Afrique de l'Ouest » (https://www.gcca.eu/) et mis en œuvre au sein de l'Institut de l'Environnement et de Recherche Agricoles (INERA). Que ces institutions trouvent ici l'expression de ma profonde gratitude.

Déclaration de divulgation
Les auteurs déclarent qu'il n'y a aucun conflit d'intérêt.

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Accès aux données de cette étude
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Annexe 1.
Effectif de la population par village et échantillonnage. Source : RGPH, 2006 et données terrain.
Population by village and sample. Source: RGPH, 2006 and field data.

Commune	Village	Effectif de la population en 2006 (RGPH)	Taille de l'échantillon (n)
TENADO	Tialgo	6 890	34
	Tiogo	3 083	30
	Tiogo-Mouhoun	338	15
	Tio	2 752	27
	Ténado-Centre	3 432	30
KYON	Essapoum	2 436	26
	Kyon	9 806	36
	Négarpoulo	2 094	25
	Po	1 984	20
	Poa	2 190	25
	Ziliwélé	1 880	18
ZAMO	Bwo	835	17
Total	**12**	**37 720**	**303**

Annexe 2.
Groupe d'âge des enquêtés. Source : données d'enquête, 2021.
Age group of respondents. Source: survey data, 2021.

Groupe d'âge (ans)		
Âge (ans)	Effectif	Proportion (%)
[30-34[	37	12,2
[34-39[	48	15,8
[39-44[	43	14,2
[44-49[	50	16,5
[49-54[	44	14,5
[54-59[	38	12,5
[60 et plus	43	14,2
Total	**303**	**100**

Annexe 3.
Matrice de transition des unités d'occupation des terres entre 1990 et 1999. Les valeurs du tableau représentent des superficies (unité : ha). Les valeurs en gras dans les cellules de la diagonale indiquent la stabilité de superficie des unités entre 1990 et 1999.
Transition matrix of land use units between 1990 and 1999. The values in the table represent areas (unit: ha). The bold values in the diagonal cells indicate the stability of the area of the units between 1990 and 1999.

Type d'occupation des terres en 1990	Type d'occupation des terres en 1999						
	Cultures pluviales et territoires agroforestiers	Forêt galerie	Savane arborée	Savane arbustive	Sols nus	Surface en eau	Superficie totale (ha) en 1990
Cultures pluviales et territoires agroforestiers	**283**	7	225	97	3	1	617
Forêt galerie	36	**139**	86	43	230	393	928
Savane arborée	913	257	**14 634**	5 170	426	194	21 593
Savane arbustive	235	11	602	**3 767**	33	3	4 652
Sols nus	247	29	279	182	**921**	102	1 761
Surface en eau	1	7	10	10	83	**201**	311
Superficie totale (ha) en 1999	1 715	450	15 837	9 268	1 696	894	**29 862**

Annexe 4.
Matrice de transition des unités d'occupation des terres entre 1999 et 2009. Les valeurs du tableau représentent des superficies (unité : ha). Les valeurs en gras dans les cellules de la diagonale indiquent la stabilité de la superficie des unités entre 1999 et 2009.
Transition matrix of land use units between 1999 and 2009. The values in the table represent areas (unit: ha). The bold values in the diagonal cells indicate the stability of the area of the units between 1999 and 2009.

Type d'occupation des terres en 1999	Type d'occupation des terres en 2009						
	Cultures pluviales et territoires agroforestiers	Forêt galerie	Savane arborée	Savane arbustive	Sols nus	Surface en eau	Superficie totale (ha) en 1999
Cultures pluviales et territoires agroforestiers	**658**	7	607	309	123	12	1 715
Forêt galerie	118	**176**	81	0	41	34	450
Savane arborée	1 173	199	**12 577**	1 425	431	31	15 837
Savane arbustive	757	42	2 792	**5 476**	200	2	9 268
Sols nus	141	128	182	32	**1 157**	57	1 696
Surface en eau	11	162	11	7	119	**584**	894
Superficie totale (ha) en 2009	2 858	714	16 250	7 250	2 070	720	**29 862**

Annexe 5.
Matrice de transition des unités d'occupation des terres entre 2009 et 2019. Les valeurs du tableau représentent des superficies (unité : ha). Les valeurs en gras dans les cellules de la diagonale indiquent la stabilité de superficie des unités entre 2009 et 2019.
Transition matrix of land use units between 2009 and 2019. The values in the table represent areas (unit: ha). The bold values in the diagonal cells indicate the stability of the area of the units between 2009 and 2019.

Type d'occupation des terres en 2009	Type d'occupation des terres en 2019						
	Cultures pluviales et territoires agroforestiers	Forêt galerie	Savane arborée	Savane arbustive	Sols nus	Surface en eau	Superficie totale (ha) en 2009
Cultures pluviales et territoires agroforestiers	**2 121**	3	459	218	55	1	2 858
Forêt galerie	125	**244**	211	9	108	18	714
Savane arborée	3 083	38	**8 995**	3 876	214	44	16 250
Savane arbustive	1 822	1	1 519	**3 849**	57	1	7 250
Sols nus	421	18	245	204	**1 160**	23	2 070
Surface en eau	62	168	19	2	91	**378**	720
Superficie totale (ha) en 2019	7 635	472	11 448	8 158	1 685	464	**29 862**

Annexe 6.
Matrice de confusion des images classifiées de la Forêt classée de Tiogo en 1990.
Confusion matrix for classified images of the Tiogo Forest Reserve in 1990.

	Se	CPTA	FG	Sn	Sa	SA	Total	EC
Se	41	1	0	0	40	41	123	0,67
CPTA	0	330	0	6	3	0	339	0,03
FG	0	0	108	0	100	124	332	0,67
Sn	0	0	0	102	7	0	109	0,06
Sa	0	30	0	0	461	97	588	0,22
SA	0	0	12	0	0	910	922	0,01
Total	**41**	**361**	**120**	**108**	**611**	**1 172**	**2 413**	
EO	**0**	**0,09**	**0,1**	**0,06**	**0,25**	**0,22**		

Se : surface en eau ; CPTA : cultures pluviales et territoires agroforestiers ; FG : forêt galerie ; Sn : sols nus ; Sa : savane arbustive ; SA : savane arborée ; EC : erreur de commission ; EO : erreur d'omission.

Annexe 7.
Matrice de confusion des images classifiées de la Forêt classée de Tiogo en 1999.
Confusion matrix for classified images of the Tiogo Forest Reserve in 1999.

	Se	CPTA	FG	Sn	Sa	SA	Total	EC
Se	347	0	0	0	0	0	347	0
CPTA	0	377	2	0	0	0	379	0,005
FG	0	1	63	0	0	58	122	0,484
Sn	0	0	0	207	0	0	207	0
Sa	0	0	0	0	611	0	611	0
SA	0	0	13	0	0	1 005	1 018	0,013
Total	**347**	**378**	**78**	**207**	**611**	**1 063**	**2 684**	
EO	**0**	**0,002**	**0,192**	**0**	**0**	**0,054**		

Se : surface en eau ; CPTA : cultures pluviales et territoires agroforestiers ; FG : forêt galerie ; Sn : sols nus ; Sa : savane arbustive ; SA : savane arborée ; EC : erreur de commission ; EO : erreur d'omission.

Annexe 8.
Matrice de confusion des images classifiées de la Forêt classée de Tiogo en 2009.
Confusion matrix for classified images of the Tiogo Forest Reserve in 2009.

	Se	CPTA	FG	Sn	Sa	SA	Total	EC
Se	245	0	0	0	0	0	245	0
CPTA	0	346	0	0	0	0	346	0
FG	0	0	197	0	0	1	198	0,005
Sn	0	0	0	159	0	0	159	0
Sa	0	0	0	0	259	0	259	0
SA	0	0	4	0	0	138	142	0,028
Total	**245**	**346**	**201**	**159**	**259**	**139**	**1 349**	
EO	**0**	**0**	**0,02**	**0**	**0**	**0,01**		

Se : surface en eau ; CPTA : cultures pluviales et territoires agroforestiers ; FG : forêt galerie ; Sn : sols nus ; Sa : savane arbustive ; SA : savane arborée ; EC : erreur de commission ; EO : erreur d'omission.

Annexe 9.
Matrice de confusion des images classifiées de la Forêt classée de Tiogo, Burkina Faso, en 2019.
Confusion matrix for classified images of the Tiogo Forest Reserve, Burkina Faso, in 2019.

	Se	CPTA	FG	Sn	Sa	SA	Total	EC
Se	292	0	0	0	0	0	292	0
CPTA	0	260	0	0	12	0	272	0,044
FG	0	0	247	0	0	13	260	0,050
Sn	0	0	0	132	0	0	132	0
Sa	0	0	0	0	725	0	725	0
SA	0	0	14	0	3	436	453	0,038
Total	**292**	**260**	**261**	**132**	**740**	**449**	**2 134**	
EO	**0**	**0**	**0,054**	**0**	**0,02**	**0,03**		

Se : surface en eau ; CPTA : cultures pluviales et territoires agroforestiers ; FG : forêt galerie ; Sn : sols nus ; Sa : savane arbustive ; SA : savane arborée ; EC : erreur de commission ; EO : erreur d'omission.

Références

Ahononga F. C., Gouwakinnou N. G., Sorotori H. S. S., Biaou H., Biaou S., 2020. Facteurs socio-économiques expliquant la déforestation et la dégradation des écosystèmes dans les domaines soudanien et soudano-guinéen du Bénin. Annales de l'Université de Parakou, Série Sciences Naturelles Agronomiques, 10 (No.2) : 43-60. https://doi.org/10.56109/aup-sna.v10i2.36

Akoguhi P.N., Dibi H. N., Godo M. H., Adja G. M., Kouamé F. K., 2022. Évaluation des méthodes de classifications dirigées (spectrale et orientée objet) sur les images satellitaires à THRS. Cas de la cartographie du tissu urbain de la commune de Cocody et d'Attécoubé (Abidjan, Côte d'Ivoire). VertigO, 22 (3). https://doi.org/10.4000/vertigo.36548

Belem M., Zoungrana M., Nabaloum M., 2018. Les effets combinés du climat et des pressions anthropiques sur la forêt classée de Toéssin, Burkina Faso. International Journal of Biological and Chemical Sciences, 12 (5): 2186-2201. https://doi.org/10.4314/ijbcs.v12i5.20

Bernier B., 1992. Introduction à la Macroéconomie. Dunod, 217 p.

Brun E. L., Sinasson G., Azihou A. F., Gibigaye M., Tente H. A. B., 2020. Perceptions des facteurs déterminants de dégradation de la flore des zones humides dans la commune d'Allada, Sud-Bénin. Afrique Science, 16 (4) : 5267.

Chave J., Réjou-Méchain M., Búrquez A., Chidumayo E., Colgan M. S., Delitti W. B. C., *et al.*, 2014. Improved allometric models to estimate the aboveground biomass of tropical trees. Global Change Biology, 20 (10): 3177-3190. https://doi.org/10.1111/gcb.12629

Chekchek A., Fennouh Z., 2019. Détection et extraction des surfaces d'eau à partir des données spatiales. Cas du Bassin Versant Côtier, Constantinois Ouest. Mémoire de Master en Géologie, Université de Jijel, Algérie, 91 p. https://theses-algerie.com/8819082137331296/memoire-de-master/universite-mohammed-seddik-ben-yahia---jijel/d%C3%A9tection-et-extraction-des-surfaces-d-eau-a-partir-des-donn%C3%A9es-spatiales-cas-du-bassin-ve-rsant-c%C3%B4tier-constantinois-ouest

Congalton R. G., 1991. A review of assessing the accuracy of classifications of remotely sensed data. Remote Sensing of Environment, 37 (1): 35-46. https://doi.org/10.1016/0034-4257(91)90048-B

Daou I., Coulibaly A., Sidibé A., Sangaré H., Keita I., Bolozogola Y., *et al.*, 2019. Suivi de la dynamique environnementale de 1985 à 2018 en zone soudano-sahélienne par télédétection : cas de la commune rurale de NYAMINA. Revue Ivoirienne des Sciences et Technologie, 34 : 13-24. https://www.researchgate.net/publication/338549306

Dayamba S. D., 2010. Fire, Plant-derived Smoke and Grazing Effects on Regeneration, Productivity and Diversity of the Sudanian Savanna-woodland Ecosystem. Doctoral Thesis, Swedish University of Agricultural Sciences, 73 p. https://pub.epsilon.slu.se/2365/1/Dayamba_S_D_101011.pdf

Dayamba S. D., Djoudi H., Zida M., Sawadogo L., Verchot L., 2016. Biodiversity and carbon stocks in different land use types in the Sudanian Zone of Burkina Faso, West Africa. Agriculture, Ecosystems & Environment, 216: 61-72. https://doi.org/10.1016/j.agee.2015.09.023

Dimobe K., Goetz D., Ouédraogo A., Forkuor G., Wala K., Porembski S., *et al.*, 2017. Spatio-temporal dynamics in land use and habitat fragmentation within a protected area dedicated to tourism in a Sudanian savanna of West Africa. Journal of Landscape Ecology, 10: 75-95. https://doi.org/10.1515/jlecol-2017-0011

DRAAH (Direction Régionale de l'Agriculture et des Aménagements Hydro-agricoles)/Centre-ouest du Burkina Faso, FAO, 2020. Global Forest Resources Assessment 2020 : Main report. FAO, 164 p.

Ezzine I., Zargouni F., Ghanmi M., 2012. Analyse linéamentaire des images Landsat-TM et Spot de l'Atlas Centro-septentrional : cartographie du prolongement SW de la cicatrice de Zaghouan. Télédétection, 10 (4) : 199-211. https://hal.science/hal-01948894/document

FAO, 2021. COP26 – L'expansion agricole est responsable de près de 90 pour cent de la déforestation dans le monde. FAO. https://www.fao.org/newsroom/detail/cop26-agricultural-expansion-drives-almost-90-percent-of-global-deforestation/fr

FAO, 2020. Global Forest Resources Assessment 2020: Main report. FAO, 164 p. https://doi.org/10.4060/ca9825en

FAO, 2016. Directives mondiales pour la restauration des forêts et des paysages dégradés dans les terres arides : renforcer la résilience et améliorer les moyens d'existence. FAO, 190 p. https://openknowledge.fao.org/items/2dee697f-31ff-4706-aef1-62433855422e

Fontès J., Guinko S., 1995. Carte de végétation et de l'occupation d'un sol du Burkina Faso : notice explicative. Université de Ouagadougou. Ministère de la coopération française, Projet Campus, 67 : 881-3101.

Foody G. M., 2002. Status of land cover classification accuracy assessment. Remote Sensing of Environment, 80 (1): 185-201. https://doi.org/10.1016/S0034-4257(01)00295-4

Ganamé M., 2021. Dynamique spatio-temporelle et potentiel du stock de carbone aérien des écosystèmes forestiers du Burkina Faso. Thèse de Doctorat, Université Joseph KI-ZERBO, Ouagadougou, Burkina Faso, 167 p. https://123dok.net/document/zx54nplw-dynamique-temporelle-potentiel-carbone-a%C3%A9rien-%C3%A9cosyst%C3%A8mes-forestiers-burkina.html

Gansaonré R. N., Benewindé. Zoungrana J.-B., Yanogo P. I., 2020. Dynamique du couvert végétal et implications socio-environnementales à la périphérie du parc W au Burkina Faso. VertigO, 18 (1). https://doi.org/10.4000/vertigo.20249

GIEC, 2003. Recommandations du GIEC en matière de bonnes pratiques pour le secteur de l'utilisation des terres, changements d'affectation des terres et foresterie. IGES, Kanagawa, Japon, 25 p.

INSD, 2017. Projections démographiques des communes du Burkina Faso de 2007 à 2020. Ouagadougou, Burkina Faso, INSD, 11-13. http://www.insd.bf

Institut National de la Statistique et de la Démographie (INSD), 2022. 5e RGPH, Cinquième Recensement Général de la Population et de l'Habitation du Burkina Faso. Synthèse des résultats définitifs. INSD, 186 p. http://www.insd.bf

Jiagho E. R., Kabelong Banoho L.-P.-R., Feumba R. A., 2021. Diversité de la flore ligneuse à l'intérieur du Parc National de Waza (Cameroun). International Journal of Biological and Chemical Sciences, 15 (3): 1158-1175. http://dx.doi.org/10.4314/ijbcs.v15i3.23

Kambire H. W., Djenontin I. N. S., Kaboré A., Djoudi H., Balinga M. P. B., Zida M., et al., 2015. La REDD+ et l'adaptation aux changements climatiques au Burkina Faso : causes, agents et institutions. Document Occasionnel 123. CIFOR, 112 p. https://www.cifor.org/publications/pdf_files/OccPapers/OP-123.pdf

Kpedenou K. D., Boukpessi T., Tchamie K. T. T., 2016. Quantification des changements de l'occupation du sol dans la préfecture de Yoto (Sud-Est Togo) à l'aide de l'imagerie satellitaire Landsat. Revue des Sciences de l'Environnement, Université de Lomé, Togo, 13: 137-156. https://hal.science/hal-01409418/document

Kristensen M., Balslev H., 2003. Perceptions, use and availability of woody plants among the Gourounsi in Burkina Faso. Biodiversity and Conservation, 12 (8): 1715-1739. http://dx.doi.org/10.1023/A:1023614816878

Kumar P., Dobriyal M., Kale A., Pandey A. K., Tomar R. S., Thounaojam E., 2022. Calculating forest species diversity with information-theory based indices using sentinel-2A sensor's of Mahavir Swami Wildlife Sanctuary. PLoS ONE 17 (5): 1-17. https://doi.org/10.1371/journal.pone.0268018

Ky-Dembele C., Dayamba S. D., Savadogo P., Kalinganire A., Bayala J., Muchugi A., *et al.*, 2019. Land use dictates diversity, density and regeneration of woody species in southwestern Mali, West Africa. Tropical Ecology, 60 (2): 114-122. https://doi.org/10.1007/s42965-019-00015-2

Long H., Tang G., Li X., Heilig G. K., 2007. Socio-economic driving forces of land-use change in Kunshan, the Yangtze River Delta economic area of China. Journal of Environmental Management, 83 (3) : 351-364. https://doi.org/10.1016/j.jenvman.2006.04.003

MEEVCC (Ministère de l'Environnement, de l'Économie Verte et du Changement Climatique), 2020. Contrôle de qualité et validation des cartes de couvert végétal produites par l'Institut Géographique du Burkina Faso (IGB). MEEVCC, 24 p.

Monssou E. O., Vroh B. T. A., Goné B. Z. B., Adou Y. C. Y., N'Guessan K. E., 2016. Évaluation de la diversité et estimation de la biomasse aérienne des arbres du Jardin Botanique de Bingerville (District d'Abidjan, Côte d'Ivoire). European Scientific Journal, 12 (6) : 168-184. https://doi.org/10.19044/esj.2016.v12n6p168

Ouattara B., Sanou L., Koala J., Hien M., 2022. Perceptions locales de la dégradation des ressources naturelles du corridor forestier de la Boucle du Mouhoun au Burkina Faso. Bois et Forêts des Tropiques, 352 : 43-60. https://revues.cirad.fr/index.php/BFT/article/view/36935

Ouédraogo O., Thiombiano A., Hahn-Hadjali K., Guinko S., 2008. Diversité et structure des groupements ligneux du parc national d'Arly (Est du Burkina Faso). Flora et Vegetatio Sudano-Sambesica, 11 : 5-15. https://d-nb.info/1097210448/34

Qasim M., Porembski S., Sattler D., Stein K., Thiombiano A., Lindner A., 2016. Vegetation Structure and Carbon Stocks of Two Protected Areas Within the South-Sudanian Savannas of Burkina Faso, West Africa. Environments, 3 (25) : 1-30. https://www.mdpi.com/2076-3298/3/4/25

Sambiéni K. R, Toyie M. S., Mama A., 2015. Perception paysanne sur la fragmentation du paysage de la Forêt classée de l'Ouémé Supérieur au nord du Bénin. https://doi.org/10.4000/vertigo.16477

Savadogo P., 2007. Dynamics of Sudanian Savanna-Woodland Ecosystem in Response to Disturbances. Doctoral thesis, Swedish University of Agricultural Sciences, 152 p. https://beep.ird.fr/collect/upb/index/assoc/SLU-2007-SAW-DYN/SLU-2007-SAW-DYN.pdf

Sawadogo L., 2009. Influence de facteurs anthropiques sur la dynamique de la végétation des forêts classées de Laba et Tiogo en zone soudanienne du Burkina Faso. Thèse de Doctorat, Université de Ouagadougou, Burkina Faso, 142 p.

Schwartz D., 1995. Méthode statistique théorique et appliquée, Tome 2 D., 659 p.

Soulama S., Kadeba A., Nacoulma B., Traore S., Bachmann Y., Thiombiano A., 2015. Impact des activités anthropiques sur la dynamique de la végétation de la réserve partielle de faune de Pama et de ses périphéries (sud-est du Burkina Faso) dans un contexte de variabilité climatique. Journal of Applied Biosciences, 87 (1): 8047. https://doi.org/10.4314/jab.v87i1.6

Sylla M. B., Dell'Aquila A., Ruti P. M., Giorgi F., 2010. Simulation of the intraseasonal and the interannual variability of rainfall over West Africa with RegCM3 during the monsoon period. International Journal of Climatology, 30 (12), 1865-1883. https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/joc.2029

Tankoano B., Sanon Z., Hien M., Dibi N. H., Yameogo J. T., Somda I., 2016. Pression anthropique et dynamique végétale dans la Forêt Classée de Tiogo au Burkina Faso: Apport de la Télédétection. Tropicultura, 34 (2): 193-207. http://www.tropicultura.org/text/v34n2/193.pdf

Tiendrebeogo N. R., Ouoba P., Bastide B., Nacoulma M. Y. B., Ouoba Y. H., Djiuguemde F., *et al.*, 2022. Influence des attributs forestiers sur le stock de carbone des unités de végétation sud-soudaniennes au Burkina Faso, Afrique de l'Ouest. International Journal of Innovation and Applied Studies, 38 (2) : 271-285. https://ijias.issr-journals.org/abstract.php?article=IJIAS-22-258-01

Tilahun A., Islam Z., 2015. Google Earth for Land Use Land Cover Change detection in the case of Gish Abbay Sekela, West Gojjam, Amhara State, Ethiopia. International Journal of Advancement in Remote Sensing, 3 (2): 80-87. https://www.researchgate.net/publication/317402059

Tindano E., Poremski S., Koehler J., Thiombiano A., 2021. Ecological and floristic characterization of inselberg habitats in Burkina Faso. Caractérisation écologique et floristique des habitats des inselbergs du Burkina Faso. Geo-Eco-Trop., 45 (4) : 573-588. https://www.geoecotrop.be/uploads/publications/pub_454_05.pdf

Traoré S., 2008. Impact des termitières épigées sur la régénération et la dynamique des écosystèmes de savanes : cas de la forêt classée de Tiogo, Burkina Faso. Thèse de doctorat, Université de Ouagadougou, Burkina Faso, 193 p. https://beep.ird.fr/collect/upb/index/assoc/SVT-2008-TRA-IMP/SVT-2008-TRA-IMP.pdf

Yelkouni M., 2004. Gestion d'une ressource naturelle et action collective : le cas de la forêt de Tiogo au Burkina Faso. Thèse de doctorat, Université d'Auvergne-Clermont-Ferrand I, France, 204 p. https://theses.hal.science/tel-00660993/document

Zakari S., Imorou I. T., Thomas O. A. B., Djaouga M., Arouna O., 2018. Application de la Télédétection et du SIG au suivi des formations végétales de la Forêt Classée des Trois Rivières au Nord-Est du Bénin. European Scientific Journal, ESJ, 14 (15) : 450. https://doi.org/10.19044/esj.2018.v14n15p450

Zida D., 2007. Impact of forest management regimes on ligneous regeneration in the Sudanian savanna of Burkina Faso. Thèse de Doctorat, Swedish University of Agricultural Sciences, 44 p. https://www.researchgate.net/publication/30072943_Impact_of_Forest_Management_Regimes_on_Ligneous_Regeneration_in_the_Sudanian_Savanna_of_Burkina_Faso

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Diffusion properties of Gabonese tropical hardwoods and European softwoods measured with low-tech equipment and by an inverse method

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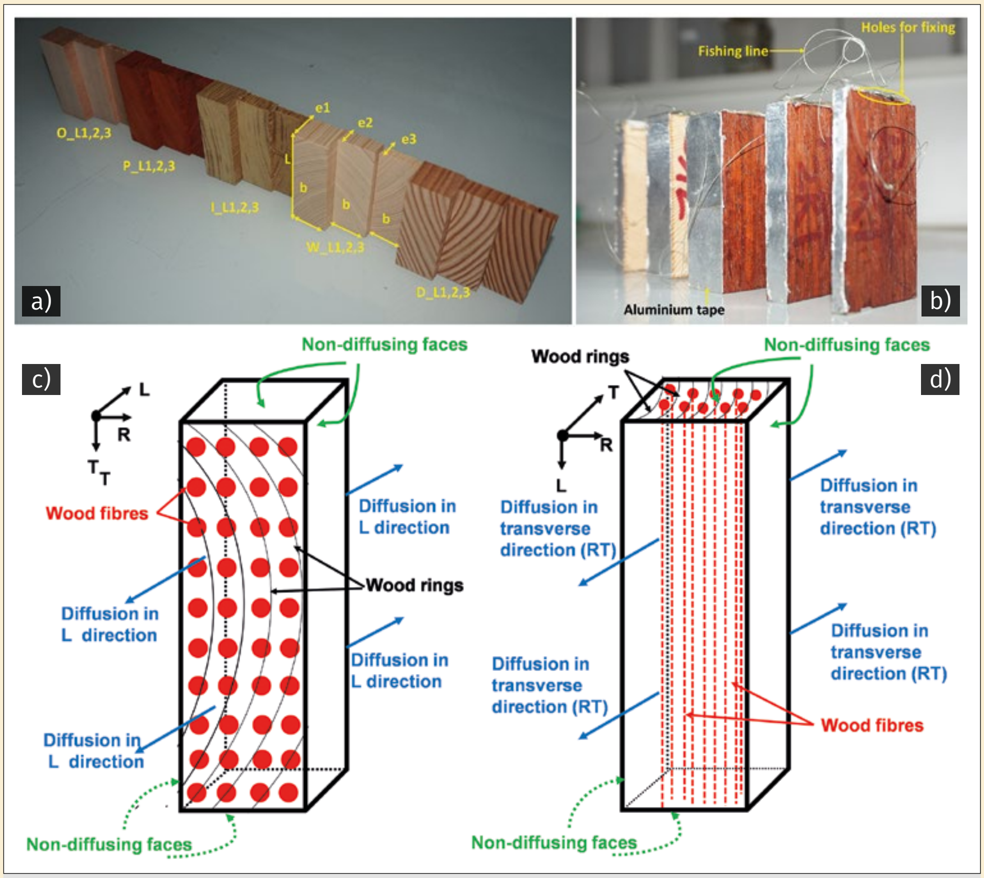

Figures 1.
Tested specimens: (a) different types and geometries of specimens; (b) specimens prepared with insulating tape (to allow a unidirectional diffusion) and fishing line (to be hanged during mass measurement); (c) geometry and direction of diffusion for specimens orientated in the L direction; (d) geometry and direction of diffusion for specimens orientated in the transverse direction RT.

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RÉSUMÉ

Mesure de la diffusion dans le bois des feuillus tropicaux du Gabon et des résineux européens à l'aide de moyens à faible technicité et par méthode inverse

Cet article présente une approche expérimentale appliquée à l'étude des propriétés de sorption et de diffusion du bois. Cinq essences de bois - trois feuillus tropicaux africains, le padouk, l'okoumé et l'iroko, et deux résineux tempérés, le sapin blanc et le Douglas - ont été étudiées en mode adsorption. Des échantillons d'une épaisseur longitudinale (L) de 10 mm et transversale (RT) de 20 mm ont été imperméabilisés sur leurs côtés afin de forcer la diffusion dans ces directions. Après séchage, les échantillons ont été suspendus sous couvert par des fils de nylon dans une boîte fabriquée artisanalement dans laquelle des solutions salines assuraient une humidité relative (HR) constante, puis conditionnés par étapes successives à 43, 55, 75, 84 et 97 % HR, la température étant maintenue entre 20 et 24 °C. Au cours des étapes d'équilibrage, les échantillons ont été périodiquement pesés sans modifier les conditions environnementales imposées, en passant le fil de nylon à travers un petit trou dans le couvercle de la boîte pour suspendre l'échantillon à un peson. Les propriétés de l'isotherme de sorption et les paramètres de diffusion ont été obtenus par une méthode inverse basée sur l'optimisation d'un modèle 1D aux différences finies. Les paramètres obtenus montrent une corrélation décroissante entre le coefficient de diffusion et la densité, comme l'ont observé plusieurs auteurs dans la littérature. Ils illustrent également l'impact des extractibles sur les paramètres de l'isotherme de sorption. Ces résultats démontrent que les essences tropicales à forte densité ou à forte teneur d'extractibles se comportent très différemment des résineux européens, ce qui empêche l'utilisation pour ces essences des normes d'équilibre de l'Eurocode 5.

Mots-clés : Coefficient de diffusion, taux d'humidité d'équilibre, méthode aux différences finies, méthode inverse, essences tropicales, Gabon.

ABSTRACT

Diffusion properties of Gabonese tropical hardwoods and European softwoods measured with low-tech equipment and by an inverse method

This paper presents an experimental approach to studies of the sorption and diffusion properties of wood. Five timber species - three African tropical hardwoods, Padauk, Okoume and Iroko, and two temperate softwoods, Silver fir and Douglas fir - were studied in adsorption mode. Specimens with 10- and 20-mm longitudinal (L) and transverse (RT) thickness were waterproofed on their sides to force diffusion in those directions. After kiln drying, the specimens were hung with nylon wires under cover in a home-made box in which salt solutions provided constant relative humidity (RH) and conditioned at 43, 55, 75, 84, and 97% RH in successive steps. Temperature was maintained between 20 and 24 °C. During the equilibration steps, the samples were periodically weighed, without altering the environmental conditions imposed, by hanging the nylon wire to a spring gauge through a small hole in the box cover. The sorption isotherm properties and diffusion parameters were obtained using an inverse method based on optimisation of a 1D finite difference model. The parameters obtained show a decreasing correlation between diffusion coefficient and density, as observed by several authors in the literature. They also illustrate the impact of extractives on the sorption isotherm parameters. These results show that tropical species with high density or many extractives behave very differently to European softwoods, which impedes the application of Eurocode 5 equilibrium standards for these species.

Keywords: Diffusion coefficient, equilibrium moisture content, finite-difference method, inverse method, tropical timber species, Gabon.

RESUMEN

Propiedades de difusión de la madera dura tropical gabonesa y de la madera resinosa europea medidas con equipamiento de baja tecnología y método inverso

Este artículo presenta un enfoque experimental en los estudios de las propiedades de sorción y difusión de la madera. Se estudiaron en modo adsorción cinco especies de madera: tres maderas duras tropicales africanas, narra, ocume e iroco, y dos maderas resinosas de clima templado, abeto balsámico y abeto de Douglas. Se impermeabilizaron lateralmente muestras con un grosor de 10 mm longitudinal (L) y 20 mm transversal (RT) para forzar la difusión en estas direcciones. Después de un secado en horno las muestras se colgaron de hilos de nilón bajo cubierto en una caja construida a mano donde soluciones salinas proporcionaban una humedad relativa constante (RH), programada con RH del 43, 55, 75, 84 y 97 % en etapas sucesivas. La temperatura se mantuvo entre 20 y 24°C. Durante los pasos de equilibrado las muestras se pesaron periódicamente sin alterar las condiciones ambientales impuestas, colgando el hilo de nilón de un dinamómetro a través de una pequeña abertura en la cubierta de la caja. Las propiedades de sorción isoterma y los parámetros de difusión se obtuvieron utilizando un método inverso basado en la optimización de un modelo 1D de diferencia finita. Los parámetros obtenidos muestran una correlación decreciente entre el coeficiente de difusión y la densidad, lo que coincide con las observaciones de varios autores en la literatura. Esto también ilustra el impacto del material extractivo en los parámetros de sorción isoterma. Estos resultados muestran que las especies tropicales con elevada densidad o mucho material extractivo se comportan de forma diferente a las maderas resinosas europeas, lo que impide la aplicación de las normas de equilibrio del Eurocódigo 5 para estas especies.

Palabras clave: Coeficiente de difusión, contenido de humedad en equilibrio, método de diferencia finita, método inverso, especies madereras tropicales, Gabón.

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Introduction

Wood is a hygroscopic material; its mechanical and physical properties depend highly on its water content (Merakeb et al. 2009; Liu et al. 2020; Engonga Edzang et al. 2020). The study of water transfer in porous material from a theoretical and experimental point of view has been widely addressed in the past (Stamm 1959; Comstock 1963; Rosen 1978; Siau and Avramidis 1996; Agoua et al. 2001) with formulations based on Fick's laws. In the wood, water is present in the form of free water, as liquid or vapour in the lumens, and as bound water in the cell walls (Kollman and Côté 1968; Varnier et al. 2020). Knowledge of water movement properties such as diffusion coefficients allows for better estimating the flux of water desorbed or adsorbed (Mouchot 2002). These properties are involved in several processes, such as wood drying and chemical treatment (Choong and Skaar 1972; Agoua and Perré 2010). A good characterisation of the diffusion process requires the development of reliable experimental techniques. To date, there are several techniques and experimental methods to monitor the evolution of moisture content (MC) in wood in transient and steady states, including the weighing method and electrical methods (Mouchot 2002). Some of these techniques sometimes require taking the wood out of the enclosure and weighing it on a scale to estimate its mass, which may disturb the MC history of the tested specimens.

Studies on the hydric behaviour of tropical woods are still quite rare in the literature. Manfoumbi Boussougou et al. (2014) addressed the use of Eurocode 5 in the verification of wood constructions and their dimensioning in tropical environments. Alkadri et al. (2020) measured the hygromechanical properties of Grenadilla wood (*Dalbergia melanoxylon*); Simo-Tagne et al. (2016) can also be mentioned. These different studies are still insufficient and do not provide useful information to improve the correct use of tropical woods and promote their use. This makes it difficult to integrate tropical woods into construction projects, as the application of current recommendations such as Eurocode 5 does not consider the hydric properties of tropical woods in given contexts (Benoit et al. 2019). This is justified by the lack of data on tropical woods in the literature.

The purpose of this paper is twofold: to propose an experimental approach for transient mass monitoring of wood specimens and to characterise the hydric properties of three tropical species in comparison to two temperate references. The experimental setup allows measurements to be made on many specimens without disturbing the water status of the system in which the specimens are placed.

Material and Methods

Material

The work was carried out on a total of 60 wood specimens, including 3 tropical hardwoods, Okoume (O, *Aucoumea klaineana*), Padauk (P, *Pterocarpus soyauxii*), and Iroko (I, *Milicia excelsa*), and 2 temperate softwoods, Silver fir (SF, *Abies alba*) and Douglas fir (DF, *Pseudotsuga menziesii*). These specimens are installed into a test box with relative humidity (RH) regulated using saline solutions, itself placed in a room regulated in temperature (T) at about 20 °C.

The tests were performed on wood specimens of different thicknesses: *e*1 = 20 mm and *e*2 = 10 mm, as shown in figure 1a. The thinnest specimens (*e3* = 5 mm) are not used for further analysis because their mass measurements were too noisy. The measurements were carried out using a 100 g load cell. It was observed that the measurement system was unable to measure the masses of low-mass samples (around 4.3 ± 1.2 g) with sufficient accuracy. For each species, the thickness of the specimens was orientated along the longitudinal (L) or transverse (RT) direction; this latter designation means that no difference was made between the radial and tangential directions. To force the diffusion in the L or RT direction, the other 4 faces were covered with 3 layers of aluminium tape (figure 1b). On one of the upper sides of the test specimens, a space was left to attach to it a fishing line. Table I shows the dimensions and density of specimens tested in both directions. Density was measured after the samples were assumed stabilised in a constant environment of 20 °C and 43% relative humidity. The geometry and diffusion direction for specimens orientated in the L and RT directions are provided in figures 1c and 1d.

Table I.
Dimensions and density of tested specimens.

Specimen type	Thickness e (mm)	Width B (mm)	Length L (mm)	Density				
				Silver fir	Douglas fir	Okoume	Padauk	Iroko
L1	20	24	65	0.48 ± 0.01	0.49 ± 0.06	0.44 ± 0.01	0.50 ± 0.01	0.50 ± 0.01
L2	10							
RT1	20							
RT2	10							

Nomenclature

Abbreviations (straight letters):

DF	Douglas fir
EMC	Equilibrium moisture content [%]
FSP	Fiber saturation point
I	Iroko
L	Longitudinal direction
MC	Moisture content
O	Okoume
P	Padauk
RH	Air relative humidity [%]
WRMS	Weighted root mean square
RT	Radial-tangential direction (transverse)
SF	Silver fir
T	Air temperature [°C]

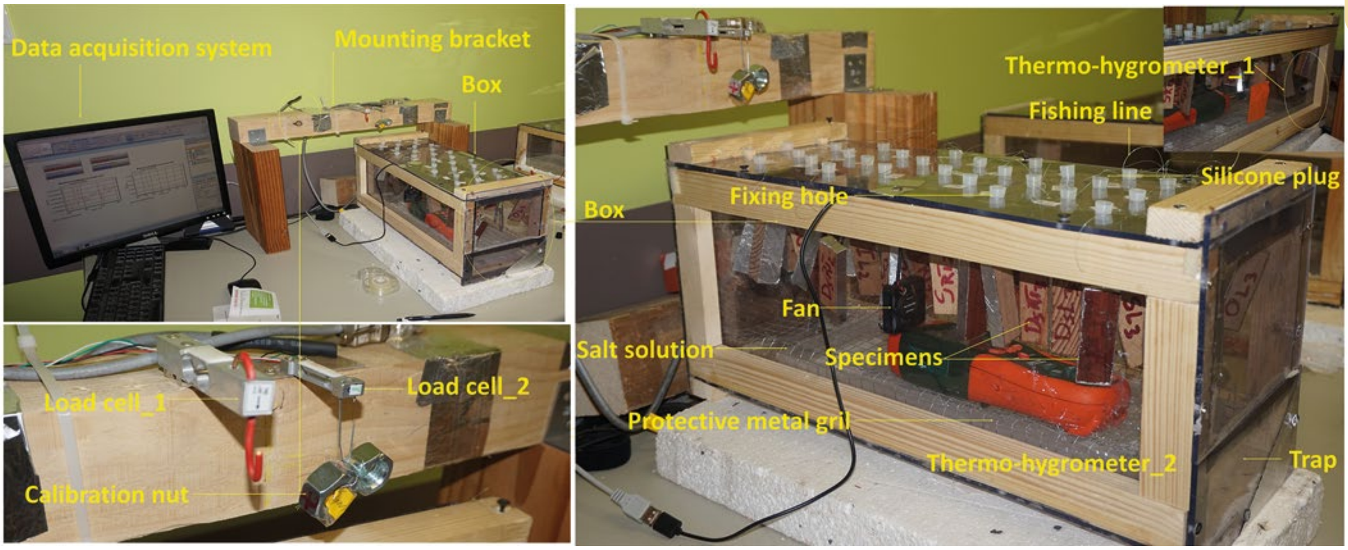
Variables

$\underline{\underline{A}}$	Second-order tensor of the implicit-Euler matrix problem
a_{ad}, φ_{ad}	Empirical parameters for the adsorption isotherm
$\alpha, \ldots, \mathrm{A}$	Mass measurement number, given as index
$\underline{b}$	Firs-order tensor of the implicit-Euler matrix problem
$\beta, \ldots, \mathrm{B}$	Humidity level number given either as index or as exponent
B	Height [mm]
D_x	Diffusion coefficient in x direction [m.s^{-2}]
$\overline{D}_j^n$	Geometric mean of the diffusion coefficient during time step n, at position j
e	Thickness [mm]
h	Half thickness [mm]
$j = 1, \ldots, J + 1$	Node number of the meshed problem, given as index
k_{Dx}	Dimensionless coefficient of the exponential relation between D_x and w
L	Length [mm]
m	Mass of a specimen measured with the load cell [g]
m_0	Initial mass [g]
m_{01}	Oven-dry mass of a specimen [g]
m_{02}	Second oven-dry mass, the specimen being covered with aluminum tape [g]
m_p, m_q	Calibration masses [g]
$n, \ldots, N$	Time number of the meshed problem, given as exponent
p, q, m	Measurements given by the force cell of the calibration masses and for a given specimen [mV.V^{-1}]
S_x	Surface exchange coefficient in the x direction [m.s^{-1}]
t	Time [s]
w_j^n, $\overline{w}$	Moisture content at time n and position, average moisture content [%]
w_e	Equilibrium moisture content [%]
w_{surf}	Moisture content on the surface of the test piece [%]
μ	Measurement given by the force cell for a given specimen (mV.V^{-1})
x	Spatial direction

Experimental setup

The experimental device (figure 2) consists of a Plexiglas box of dimensions 45 × 20 × 20 cm^3 for sample conditioning and a mobile arm equipped with a load cell for the manual measurement of the mass of the specimens at regular intervals. The range of the load cell is 100 g. The ambience of the box is controlled using the saturated salt solutions reported in table II. The boxes are equipped with a thermo-hygrometric sensor monitoring RH and T.

The experimental box was equipped with a fan to allow air circulation and ensure a uniform RH inside the box. It was turned off during mass measurements to avoid turbulence influencing the measurement. The box was also equipped with a metal grid to prevent the samples from falling into the salt solution tank. The samples were held in place by a fishing line exiting through 10 mm diameter holes in the top of the box, closed with conical silicone plugs locking the line in place. The cap of each sample was removed only for the duration of its mass measurement,



Figures 2.
Experimental setup for diffusion tests.

which greatly reduced air exchange between the inside of the box and the room. The box was conditioned using 6 salt solutions, according to the NF EN ISO 483 standard (2006), with expected RH levels of 43%, 57%, 75%, 84%, and 97%. The first step was to check the system reliability in conditioning the specimens at constant RH and T. Table II presents the values of RH and T observed in the box during the experimental phase. According to the standard, whether at T = 20 °C or T = 25 °C, we should find the same RH with the saline solutions used. This was confirmed by the results presented in table II: the RH values oscillated with a small standard deviation close to those expected by the standard, although small temperature variations occurred.

Sample preparation and mass measurement

After machining, the specimens were dried at 104 °C to estimate their oven-dry mass m_{01}. Once m_{01} was reached, the specimens were covered with adhesive aluminium tape and attached to a fishing line for later fixation. They were dried again at 104 °C to get a second oven-dry mass m_{02}, including tape and wire. After these two steps, the specimens were placed in the boxes for mass monitoring in a predefined order (O, P, SF, DF, I), starting with the specimens of the smallest thickness and moving toward the largest. Mass measurements were started as soon as possible from the beginning of each humidity level. The estimation of the mass m in grammes of a specimen was obtained by measuring the load cell output electrical signal m (in mV.V^{-1}) of a wooden specimen and those of two metal bolts used as calibration mass, p and q, given by the load cell (Equation 1):

$$m = m_p + \frac{m_q - m_p}{q - p}(\mu - p) \qquad (1)$$

where m_p and m_q are the standard masses of the bolts previously determined on a precision balance (error less than 10^{-6} g). To avoid a possible drift, the calibration signals (p and q) are re-evaluated every 10 measurements using the reference masses (metal nuts). This procedure allowed an accuracy of 0,01% or 0,01 g, despite the use of a low-cost load cell. After obtaining the mass m, the evolution of the mean moisture content (MC, $\overline{w}$) of a specimen over time is given by (Equation 2):

$$\overline{w}(t) = \frac{m(t) - m_{02}}{m_{01}} \qquad (2)$$

Table II.
Aqueous solutions used with expected relative humidity (RH) at temperature (T) of 20-25°C and measured climatic conditions.

Aqueous solution	RH (%) NF EN ISO 483	RH (%)	T (°C)
Potassium carbonate K_2CO_3	43	42.0 (± 0.4)	20.6 (± 0.5)
Sodium bromide NaBr	57	57.8 (± 1.1)	23.7 (± 0.5)
Sodium chloride NaCl	75	73.5 (± 1.3)	23.8 (± 0.4)
Potassium chloride KCl	84	83.4 (± 0.6)	23.9 (± 0.7)
Potassium sulfate K_2SO_4	97	94.8 (± 1.1)	23.3 (± 1.4)

Diffusion model

During the previously described experiment, water vapour and bound water diffusion occur and these processes can be described, for a unidirectional flow along x direction, using second Fick's law (Equation 3):

$$\frac{\partial w}{\partial t} = \frac{\partial}{\partial x}\left(D_x \frac{\partial w}{\partial x}\right) \qquad (3)$$

where D_x is the diffusion coefficient in the direction of the water flow and w is the local MC, a function of position x and time t. The diffusion coefficient D_x depends on w. In the transverse direction, D_{RT} is exponentially increasing with w, while in the longitudinal direction D_L it is exponentially increasing at low w and then exponentially decreasing with w (Siau 1984). Neglecting the increasing part of D_L this can be expressed by (Equation 4):

$$D_{RT}=D_{RT0}.e^{k_{DRT}w};D_L=D_{L0}.e^{k_{DL}w} \quad (4)$$

where D_{RT0} and D_{L0} are the diffusion coefficient when $w = 0$, k_{DL} and k_{DRT} are the exponential factor relating D with w, k_{DL} being negative. Thybring et al. (2022) explain that phenomenon by the water mobility increasing when MC increases, possibly due to the decrease of the activation energy needed to break a hydrogen bond.

The boundary conditions use convection at one end and symmetrical geometry, leading to moisture content flux null at the other end. The convection process is described combining Newton's law for convection and first Fick's law (Equation 5):

$$D_x\frac{\partial w}{\partial x}=S(w_e-w_{surf}) \quad (5)$$

where S is the surface exchange coefficient, w_e and w_{surf} represent the equilibrium moisture content (EMC) and the sample surface's MC, respectively. w_e is the MC towards which wood MC tends in a given environment (RH, T). It follows a sorption hysteresis as it depends on the wood MC history and whether it is adsorbing or desorbing. The hysteresis is bounded by the so-called isotherm envelope, which was modelled by Merakeb et al. (2009) (Equation 6):

$$\ln\left(\frac{w_e}{w_s}\right)=\varphi_i\ln(RH).e^{a_i.RH} \quad (6)$$

where w_s is the saturation MC, i.e., the Fiber Saturation Point (FSP), φ_i and a_i are empirical parameters that fit the isotherm envelopes. Considering only adsorption starting from $w = 0$, as it is the case in this study, $\varphi_i=\varphi_{ad}$ and $a_i = a_{ad}$. These 3 parameters depend on temperature and wood species. The symmetrical condition leads to $\partial w/\partial x=0$.

Finite-difference approximation

A finite difference approximation is chosen to resolve the partial differential equation (3) as it is simple and efficient for 1D diffusion problems. A so-called θ-scheme is used with $\theta = 1/2$, corresponding to a Crank-Nicolson method that is unconditionally stable. Every sample is discretised in $(J + 1)$ nodes (specified by index j) with a constant distance $\Delta x = x_j - x_{j-1} = 0.1$ mm. Time is specified using exponent n (N is the last instant), where the time step is refined when a humidity level is applied and then progressively unrefined until the next step, but never exceeding $\Delta t = 3600$ seconds. Mathematically, it can be written $\Delta t = \min(2^k, 3600)$ where $k = 1,2,3, \dots, K$; and k is reset when a new humidity level starts. Equation (3) can hence be approximated by (Equation 7):

$$\frac{w_j^n-w_j^{n-1}}{\Delta t}=\frac{\theta}{\Delta x^2}\left[\overline{D}_{j+\frac{1}{2}}^{n-1}(w_{j+1}^n-w_j^n)-\overline{D}_{j-\frac{1}{2}}^{n-1}(w_j^n-w_{j-1}^n)\right]+\frac{(1-\theta)}{\Delta x^2}\left[\overline{D}_{j+\frac{1}{2}}^{n-1}(w_{j+1}^{n-1}-w_j^{n-1})-\overline{D}_{j-\frac{1}{2}}^{n-1}(w_j^{n-1}-w_{j-1}^{n-1})\right] \quad (7)$$

where $\overline{D}_{j\mp\frac{1}{2}}^{n-1}$ is the geometric mean of the diffusion coefficient at time n - 1 and between x_j and $x_{j\pm1}$ (Equation 8):

$$\overline{D}_{j+1/2}^{n-1}=\sqrt{D_j^{n-1}.D_{j+1}^{n-1}}$$
$$\overline{D}_{j-1/2}^{n-1}=\sqrt{D_j^{n-1}.D_{j-1}^{n-1}} \quad (8)$$

where $D_j^{n-1}=D_0.e^{kw_j^{n-1}}$. Note that the diffusion coefficient calculation remains explicit, whence $\Delta t \leq 3600$ to keep convergence. Using equation (5), the convection boundary at boundaries $j = 0$ and symmetry at $j = J + 1$ are defined in equation (9):

$$w_0^n\left(1+\frac{\overline{D}_{1/2}^{n-1}}{S.\Delta x}\right)-\frac{\overline{D}_{1/2}^{n-1}}{S.\Delta x}w_1^n=w_e^n \;\; ; \;\; w_{J+1}^n-w_J^n=0 \quad (9)$$

Equation (7) can therefore be written in matrix form (Equation 10):

$$\underline{\underline{A}}^{n-1}\underline{w}^n=\underline{b}^n \quad (10)$$

where the only unknown is the vector $\underline{w}^n$ that contains MC of all points of the sample at time n. Detailed matrix $\underline{\underline{A}}^{n-1}$ and vector $\underline{b}^n$ are given in appendix A.

Optimisation process

Diffusion properties of the presented wood are fitted so that equation (10) accurately represents the experimental results. T and RH measured in the box are directly used as input parameters to calculate w_e using equation (6). Olek and Weres (2001) point out that a so-called inverse method appears to be a valuable tool for determining the coefficients (Eriksson et al. 2006). It appears that the surface exchange coefficients S_{RT} and S_L have a very small impact on the outcome of the equation results. This means that considering the wood's external surface as immediately at equilibrium with the surrounding air is a reasonable assumption regarding the size of the samples. Therefore, S_{RT} and S_L are fixed at 10^5 m.s^{-1}, ensuring no contact resistance. The final unknowns are: (i) diffusion properties D_{0RT}, D_{0L}, k_{DRT}, k_{DL}; (ii) adsorption isotherm parameters w_s, φ_{ad}, a_{ad}. The objective function that has to be minimised is a weighted root mean square (*WRMS*) of the difference between experimental results and the finite difference approximation. As the duration between 2 humidity levels is high and diffusion is not a linear process, there are many more mass measurements when the wood is close to equilibrium compared to right after a new humidity level (i.e., transitory phase). An equilibrium state only depends on w_s, φ_{ad} and a_{ad}, thus only mass measurements in the transitory phase allow to estimate diffusion properties. Consequently, weights are added to the root mean square calculation so that the closer an experimental measurement is to the last humidity level, the bigger is its weight. This compensates for the fact that these points are fewer in number than those close to the equilibrium state. Mathematically it leads to:

$$WRMS = \sum_{\beta=1}^{B} \sum_{\alpha=1}^{A_\beta} \left(w_{\alpha,\beta}^{meas} - w_{\alpha,\beta}^{est}\right)^2 \times \left[u_{\alpha+1}^{\beta} - u_{\alpha-1}^{\beta}\right] \quad (11)$$

where β is the humidity level number (1 for 43%, 2 for 57%, etc.) ranging from 1 to B and α is the measurement number that is restarted at a new humidity level, ranging from 1 to A_β where A_β depends on the humidity level considered. This leads to the time list: $t_{1,1}, t_{2,1}, \ldots, t_{A_1,1}, t_{1,2}, t_{2,2}, \ldots\ t_{A_2,2}, \ldots\ t_{A_B,B}$. $\left(w_{\alpha,\beta}^{meas} - w_{\alpha,\beta}^{est}\right)^2$ is the squared difference between the measured and estimated moisture content, and $\left[u_{\alpha+1}^{\beta} - u_{\alpha-1}^{\beta}\right]$ is the weight factor with:

$$u_\alpha^\beta = \log\left(t_{\alpha,\beta} - t_{0,\beta}\right) \quad (12)$$

where $t_{0,\beta}$ is the starting time of the humidity level β and $t_{A_\alpha+1,\beta} = t_{0,\beta+1}$ is the starting point of the following humidity level β + 1. This function uses the decrease in the growth rate of the logarithm, which assigns a greater weight to measurement points closer to the beginning of a humidity level. The chosen weight factor ensures a balanced contribution of the different times, expressed in a logarithmic scale, to the fitting process.

The WRMS is calculated for each set of parameters so that the set that minimises the WRMS is considered representative of the material properties. A typical diffusion coefficient ranging is between 10^{-12} and 10^{-8} $m^2.s^{-1}$. It is chosen to optimise log(D) instead of its direct value. Indeed, input variations at 10^{-10} are computationally more manageable when expressed logarithmically.

The optimisation is constrained by boundaries for each parameter and uses a Nelder-Mead simplex algorithm. This algorithm is extensively documented in the literature and has already been implemented in Python's Scipy module (Gao and Han 2012). Its selection is based on its ease of use and familiarity to practitioners. However, simplex methods may be influenced by local minima. Therefore, for each species, 10 optimisation processes using 10 random initial values among the boundaries are realised. The selected minimum is the one that is physically the most realistic, in the sense that the anisotropy ratio D_L/D_{RT} should decrease with increasing density. Other optimisation methods, such as differential evolution algorithms, offer a broader scope in terms of exploring the search space and may better ensure convergence to a global optimum (Storn and Price 1997). Gradient-based algorithms are avoided as the WRMS function may not be differentiable. Initial bounds are detailed in appendix B for each parameter of each species.

Table III.
Optimised parameters and weighted root mean square (WRMS) difference of measured and modelled difference for all species

	Silver fir	Douglas fir	Okoume	Padauk	Iroko
D_{RT0} x 10^{-11} [$m^2.s^{-1}$]	1.63	2.1	1.34	0.47	1.79
k_{DRT} [-]	8.51	5.77	5.23	1.22	5.29
D_{L0} x 10^{-10} [$m^2.s^{-1}$]	9	8.09	10.9	0.6	4.78
k_{DL} [-]	-9.54	-13.1	-13.5	-1.75	-8.76
w_s [%]	24.6	24.4	24.9	15.4	19.4
φ_{ad} [-]	0.67	0.69	0.74	0.67	0.71
a_{ad} [-]	1.63	1.69	1.55	1.65	1.47
WRMS [%]	0.51	0.47	0.35	0.26	0.4

Results and discussion

Fitting of diffusion data

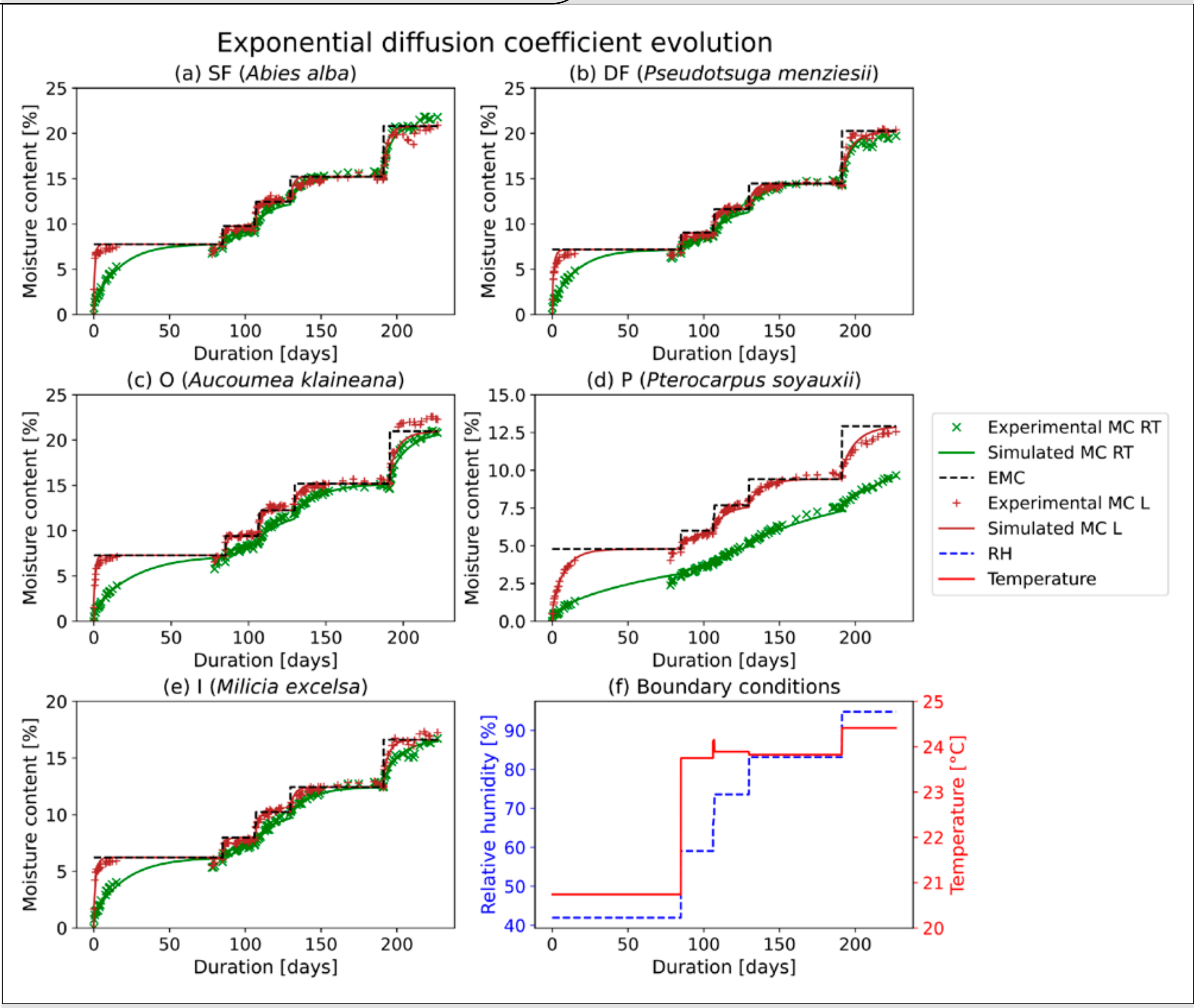
Figure 3 shows the time-evolution of MC, both for experimental and numerical results approximated after optimisation, for all specimens tested in L and RT directions. The optimised diffusion parameters, presented in Table III, accurately describe the evolution of MC with time (WRMS < 0.6% for 225 days).

It is worth noting that w_s is obtained using only adsorption results that did not reach complete saturation, hence cannot be compared with FSP values from the literature. The results highlight the anisotropy with $D_L > D_{RT}$ at any w. This hierarchy has been widely observed by several authors (Agoua and Perré 2010; Mouchot 2002) and is clearly explained by the anatomical configuration that triggers the diffusion process along the tracheids for softwoods and in the vessels for hardwoods. The anisotropy ratio D_L/D_{RT} is between 2 and 70, depending on the considered RH, which is consistent with Siau (1984) that identifies an anisotropy ratio of around 70 at w = 0% and 4 at w = 25% (figure 4). For very dense species, i.e., Padauk and Iroko, the diffusion coefficient is less influenced by moisture content variations.

Figures 5 show the relation between the measured density and diffusion coefficient when w = 8%. Though much more data would be needed to observe a strong correlation, density seems to decrease the diffusion coefficient. This hierarchy corroborates the results of Kouchade (2004) on the effect of density on diffusion, or those of Perré and Turner (2001) who noted that earlywood diffused faster than latewood. Indeed, thicker cell walls and smaller lumen diameters slow down the movement of water vapour. The markedly slower diffusion of Padauk is hence explained by its higher density.

Equilibrium moisture content and hygroscopic table of tropical woods

Based on the optimised parameters, adsorption isotherms are plotted in figure 6. The hygroscopic equilibrium chart of AFNOR (2010) and predicted EMC from Simpson (1973) are added for comparison; they are based on temperate softwood desorption. Iroko and Padauk show systematically lower EMC, possibly explained by the presence of extractives. According to the CIRAD (2015) Tropix database,



Figures 3.
Diffusion kinetics of tested species in the longitudinal (L, brown) and transverse (RT, green) direction: (a) Silver fir; (b) Douglas fir; (c) Okoume; (d) Padauk; (e) Iroko; (f) Boundary conditions (RH, T). Black dotted line: calculated EMC using equation (6) with optimised adsorption parameters (w_s, a_{ad}, φ_{ad}) and imposed (RH, T); continuous lines: Finite difference approximation; cross: measured MC.

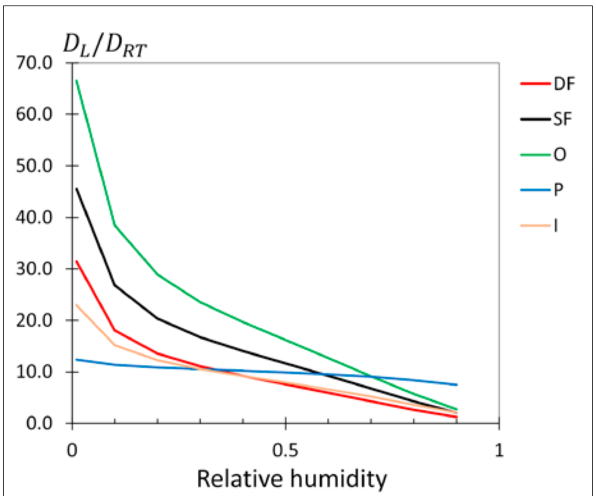
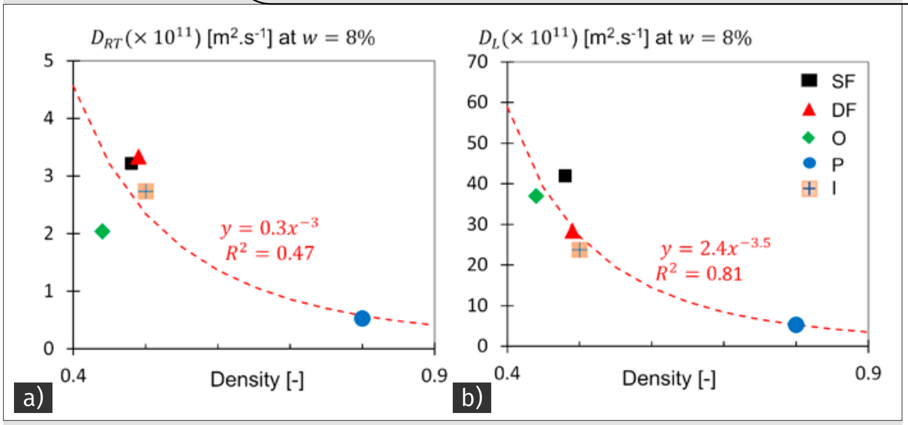


Figure 4.
Anisotropy ratio D_L/D_{RT} as a function of the relative humidity for all species. SF: Silver fir; DF: Douglas fir; O: Okoume; P: Padauk; I: Iroko.

regarding the resistance to fungi and insects such as termites, Padauk is classified as very durable and Iroko as durable to very durable. Okoume and Silver fir have low durability, Douglas fir has low to medium durability. Padauk was shown to contain more extractives than Okoume and Iroko: 9.6 ± 0.9% for Padauk (Mounguengui et al. 2016), 2.1 ± 0.1% for Okoume (Safou-Tchiama 2005), and 5.51 ± 0.11% for Iroko (Gaff et al. 2023). Several studies have shown that the durability of a species is positively related to the extractive content and the type of lignin (Highley 1982; Yamamoto and Hong 1994; Antwi-Boasiako et al. 2010), and Choong and Achmadi (1991) showed that the EMC of extractive-rich wood is lower than that of extractive-poor wood. These results show that model predictions of Simpson (1973) or charts given by NF EN 1995-1-1/NA (2010), valid for temperate softwood desorption, cannot be applied blindly to tropical species. They are particularly not suitable for species that contain many extractives such as Iroko and Padauk.



Figures 5.
Diffusion coefficient at w = 8% as a function of the measured density, for both (a) transverse and (b) longitudinal directions.

Conclusion

This paper presents an innovative experimental approach to the study of unidimensional water diffusion in wood and new diffusion data for tropical species. The tests were performed at a temperature of 20-25 °C and successive RH levels: 0, 43, 58, 74, 84, 95%. The frugal adsorption tests coupled with an inverse method based on finite difference approximation of diffusion kinetics allowed the estimation of the diffusion coefficient D_x (m².s⁻¹) and sorption isotherm parameters (w_s, φ_{ad}, a_{ad}) for Padauk, Okoume, Iroko, Silver Fir, and Douglas Fir wood. An optimisation process using Nelder-Mead simplex algorithm is applied. The objective function is a weighted RMS that compensates for the smaller amount of short-term data compared to long-term data. Simplex algorithm may be biased by local minimum, but 10 optimisations are realised, and the most physically significant is chosen and is at least a good approximation. For the European softwoods, the values of the calculated diffusion parameters are close to those of the literature. Among the tropical species tested, only Okoume and Iroko exhibited mass transfer laws similar to temperate woods, while the diffusion of Padauk is slower than Okoume and Iroko. This can be ascribed to the higher density of Padauk wood that requires the water to move through a higher quantity of cell wall and to the high content in extractives that possibly contribute to saturate cell-wall cavities. Furthermore, the anisotropy ratio D_L/D_{RT} of Padauk is less sensitive to MC than one of the other 4 species. The EMC values of Okoume were found to be close to those of European softwoods. However, these EMC values are slightly different from those predicted by the NF EN 1995-1-1/NA (2010) standard and the Simpson's model. This difference can be only partly explained by the fact that sorption hysteresis is not considered in these models. The sorption isotherm parameters of Padauk and Iroko are significantly different than those of European softwood and that is justified by the extractive content of these tropical species. Because of the very different hydric behaviour highlighted for tropical species in the future, it will be necessary to develop specific models for these species as well as specific hygroscopic equilibrium charts.

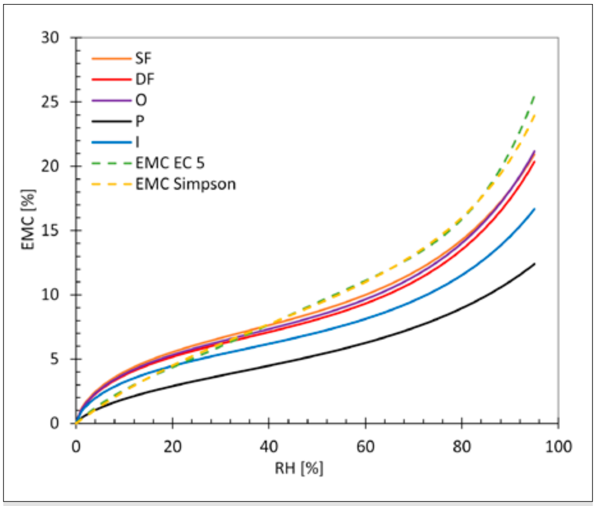


Figure 6.
Equilibrium moisture content of each species, green dashed-line NF EN 1995-1-1/NA (2010) model (EMC EC 5); yellow dashed-line Simpson (1973) model (EMC Simpson). SF: Silver fir; DF: Douglas fir; O: Okoume; P: Padauk; I: Iroko; EMC: Equilibrium moisture content [%]; RH: Air relative humidity [%].

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Access to research data
All Excel sheets of the measurements and python scripts of the analysis concerning the work presented in this article are publicly available on Zenodo: https://zenodo.org/records/13839289
Please, think to inform authors and to cite the dataset as: BONTEMPS A., 2024. Data for article BFT-Assekoetal2024_diffusion_of_tropical_hardwoods [Data set]. Zenodo. https://doi.org/10.5281/zenodo.13839289

Appendix A.
Finite-difference calculation.

Second Fick's law for unidimensional problem is approximated using implicit Euler scheme that gives the matrix problem from equation (10):

$$\underline{\underline{A}}^{n-1}\underline{w}^{n} = \underline{b}^{n} \qquad (A1)$$

where $\underline{\underline{A}}^{n-1}$ is:

$$\begin{bmatrix} 1+F_2\overline{D}_{1/2}^{n-1} & -F_2\overline{D}_{1/2}^{n-1} & 0 & 0 & & \\ -\theta F_1\overline{D}_{1/2}^{n-1} & 1+\theta F_1\left(\overline{D}_{1/2}^{n-1}+\overline{D}_{3/2}^{n-1}\right) & -\theta F_1\overline{D}_{3/2}^{n-1} & 0 & \cdots & 0 \\ 0 & -\theta F_1\overline{D}_{3/2}^{n-1} & 1+\theta F_1\left(\overline{D}_{3/2}^{n-1}+\overline{D}_{5/2}^{n-1}\right) & -\theta F_1\overline{D}_{5/2}^{n-1} & & \\ & & \vdots & & \ddots & \vdots \\ & & & & \cdots & -\theta F_1\overline{D}_{J-1/2}^{n-1} & 1+\theta F_1\left(\overline{D}_{J-1/2}^{n-1}+\overline{D}_{J+1/2}^{n-1}\right) & -\theta F_1\overline{D}_{J+1/2}^{n-1} \\ & & 0 & & \cdots & 0 & -1 & 1 \end{bmatrix}$$

with $F_1 = \Delta t/\Delta x^2$, $F_2 = 1/(S_x\Delta x)$ and:

$$\left(\underline{b}^{n}\right)^{T} = \left[w_e^n \quad 0 \quad \cdots \; F_1(1-\theta)\left[\overline{D}_{j+\frac{1}{2}}^{n-1}\left(w_{j+1}^{n-1}-w_j^{n-1}\right)-\overline{D}_{j-\frac{1}{2}}^{n-1}\left(w_j^{n-1}-w_{j-1}^{n-1}\right)\right]+w_j^{n-1} \quad \cdots \quad 0\right] \;;$$

$$\left(\underline{w}^{n}\right)^{T} = \left[w_0 \quad w_1 \quad \cdots \quad w_J \quad w_{J+1}\right]^{n} \qquad (A3)$$

All above parameters are defined in Physics of diffusion kinetics and finite difference approximation sections.

Appendix B.
Boundaries for the constrained optimisation process.

Boundaries are centered on physically coherent values based on literature (Alkadri 2020; Asseko Ella 2022; Bontemps 2023 ; Cirad (2015) Tropix Database for w_s), table B1:

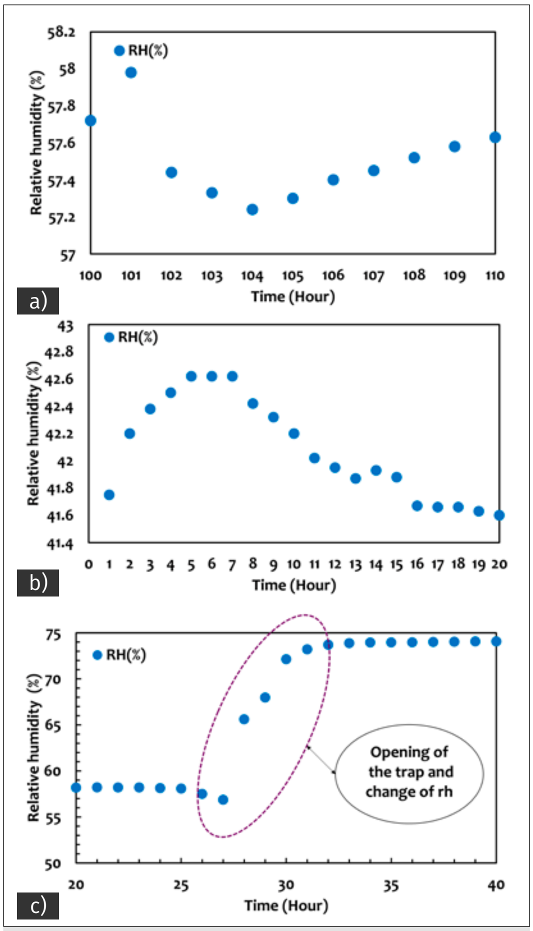
Table B1.
Centered values for the boundaries of the constrained optimisation process.

	Silver fir	Douglas fir	Okoume	Padauk	Iroko
log (D_{RT0})	-10.284	-10.441	-10.355	-11.26	-10.42
log (D_{L0})	-9.547	-9.752	-9.697	-10.31	-9.658
w_s	0.256	0.248	0.257	0.141	0.197
φ_{ad}	0.82	0.82	0.73	0.78	0.76
a_{ad}	1.435	1.435	1.636	1.16	1.413

Then boundaries are fixed such that, considering the logarithm of the optimised value, the minimum (2/3) of the centered value and the maximum is (4/3) of the centered value. This gives tremendous range thanks to the logarithm function. The boundaries of k_{DL} and k_{DRT} are: [1.10-4, 30] based on the values proposed by Siau (1984).

Appendix C.
Variations in relative humidity in the box during an experimental phase and when the trap is opened.

This figure shows the hydric condition of the box during the measurements and when the trap is opened to change the RH. The figures C1a and C1c show that the variations in RH during the measurements (opening of the Silicon caps) are low and have a small influence on the measurements. In those figures we can see that the average RH values are 42.16% ± 0.40 RH (figure C1a) and 57.24% ± 0.80 RH (figure C1b) and are very close to the values predicted by the standard. When the trap is opened, the time taken for RH to stabilise is around 3 to 4 hours (figure C1c).



Figures C1.
Hydric conditions of the box during the measurements: (a) 42% RH; (b) 58% RH; (c) opening of the trap for the change of RH.

References

Agoua E., Perré P., 2010. Mass transfer in wood: Identification of structural parameters from diffusivity and permeability measurements. Journal of Porous Media, 13 (11): 1017-1024. https://doi.org/10.1615/JPorMedia.v13.i11.80

Agoua E., Zohoun S., Perré P., 2001. A double climatic chamber used to measure the diffusion coefficient of water in wood in unsteady-state conditions: Determination of the best fitting method by numerical simulation. International Journal of Heat and Mass Transfer, 44 (19): 3731-3744. https://doi.org/10.1016/S0017-9310(01)00022-9

Alkadri A., Jullien D., Arnould O., Rosenkrantz E., 2020. Hygromechanical properties of grenadilla wood (*Dalbergia melanoxylon*). Wood Science and Technology 54: 1269-1297. https://doi.org/10.1007/s00226-020-01215-z

Antwi-Boasiako C., Barnett J. R., Pitman A. J., 2010. Relationship between total extractive content and durability of three tropical hardwoods exposed to *Coriolus versicolor* (Linnaeus) Quelet. Journal of the Indian Academy of Wood Science, 7 (1–2): 9-13. https://doi.org/10.1007/s13196-010-0002-3

Asseko Ella M., 2022. Effet de la mécanosorption et de l'hygroviscoélasticité sur la fissuration des feuillus gabonais et résineux européens. PhD Thesis, Université Clermont Auvergne, HAL, 206 p. https://theses.hal.science/tel-03953610

Benoit Y., Legrand B., Tastet V., 2019. Calcul des structures en bois – Guide d'application des Eurocodes 5 (structures en bois) et 8 (séismes) - Assemblage de pieds de poteaux. 4ème édition, Éditions Eyrolles, 540 p.

Bontemps A., 2023. Comportement mécanique des éléments de structure en bois de sapin pectiné soumis à un environnement variable. PhD Thesis, Université Clermont Auvergne, 264 p. https://theses.hal.science/tel-04151652

Choong E., Achmadi S., 1991. Effects of extractives on moisture sorption and shrinkage in tropical woods. Wood and fiber science, 23 (2): 185-196. https://wfs.swst.org/index.php/wfs/article/view/399

Choong E. T., Skaar C., 1972. Diffusivity and surface emissivity in wood drying. Wood and Fiber Science, 4 (2): 80-86. https://wfs.swst.org/index.php/wfs/article/view/399

CIRAD, 2015. Tropix 7 (version 7.5.1) – The main tecnological characteristics of 245 tropical wood species. Software database, CIRAD. https://doi.org/10.18167/74726F706978

Comstock G. L., 1963. Moisture diffusion coefficients in wood as calculated from adsorption, desorption, and steady state data. Forest Product Journal, 13 (3): 97-103. https://www.cabidigitallibrary.org/doi/full/10.5555/19636605512

Engonga Edzang A. C., Pambou Nziengui C. F., Ekomy Ango S., Ikogou S., Moutou Pitti R., 2020. Comparative studies of three tropical wood species under compressive cyclic loading and moisture content changes. Wood Material Science and Engineering, 16 (3): 193-203. https://doi.org/10.1080/17480272.2020.1712739

Eriksson J., Johansson H., Danvind J., 2006. Numerical determination of diffusion coefficients in wood using data from CT-scanning. Wood and fiber science, 2: 334-344. https://wfs.swst.org/index.php/wfs/article/view/1405

Gaff M., Kubovský I., Sikora A., Kačíková D., Li H., Kubovský M., et al., 2023. Impact of thermal modification on color and chemical changes of African padauk, merbau, mahogany, and iroko wood species reviews on advanced materials science, 62 (1): 20220277. https://doi.org/10.1515/rams-2022-0277

Gao F., Han L., 2012. Implementing the Nelder-Mead simplex algorithm with adaptive parameters. Computational Optimization and Applications, 51 (1): 259-277. https://doi.org/10.1007/s10589-010-9329-3

Highley T. L., 1982. Influence of type and amount of lignin on decay by *Coriolus versicolor*. Canadian Journal of Forest Research, 12 (2): 435-438. https://doi.org/10.1139/x82-065

Kollman F. F. P., Côte W. A., 1968. Principles of wood science and technology. 1. solid wood. Springer-Verlag, 592 p. https://link.springer.com/book/10.1007/978-3-642-87928-9

Kouchade A. C., 2004. Mass diffusity of wood determined by inverse method from electrical resistance measurement in unsteady state. PhD thesis, ENGREF (AgroParisTech), 139 p. https://pastel.hal.science/pastel-00000888/file/clement_these.pdf

Liu M., Peng L., Lyu S., Lyu J., 2020. Properties of common tropical hardwoods for fretboard of string instruments. Journal of Wood Science, 66 (1): 14. https://doi.org/10.1186/s10086-020-01862-7

Manfoumbi Boussougou N., Nguyen T. A., Angellier N., Dubois F., Ulmet L., Sauvat N., 2014. Experimental and numerical aspects in diffusion process characterization in tropical species. European Journal of Environmental and Civil Engineering, 18 (9): 963-982. https://doi.org/10.1080/19648189.2014.917993

Merakeb S., Dubois F., Petit C., 2009. Modeling of sorption hysteresis in hygroscopic materials'. Comptes Rendus – Mécanique, 337 (1): 34-39. https://doi.org/10.1016/j.crme.2009.01.001

Mounguengui S., Saha Tchinda J. B., Ndikontar M. K., Dumarçay S., Attéké C., Perrin D., et al., 2016. Total phenolic and lignin contents, phytochemical screening, antioxidant and fungal inhibition properties of the heartwood extractives of ten Congo Basin tree species. Annals of Forest Science, 73 (2): 287-296. https://doi.org/10.1007/s13595-015-0514-5

Mouchot N., 2002. Étude expérimentale et modélisation des transports diffusionnels de l'eau dans le domaine hygroscopique des bois de hêtre et d'épicéa. Thèse de doctorat, Université Henri Poincaré - Nancy 1, 232 p. https://theses.fr/2002NAN10284

NF EN ISO 483, 2006. Plastics-small enclosures for conditioning and testing using aqueous solutions to maintain the humidity at a constant value. AFNOR publishing, 10 p.

NF EN 1995-1-1/NA, 2010. Eurocode 5: Design and calculation of wooden structures - Part 1-1: general - Common rules and rules for buildings - National annex to NF EN 1995-1-1:2008 - General - Common rules and rules for buildings. AFNOR publishing, 10 p.

Olek W., Weres J., 2001. The inverse method for diffusion coefficient identification during water sorption in wood. Holzforschung, 59 (1): 38-45. https://doi.org/10.1515/HF.2005.007

Perré P., Turner I., 2001. Determination of the material property variations across the growth ring of softwood for use in a heterogeneous drying model. Part 2. Use of homogenisation to predict bound liquid diffusivity and thermal conductivity. Holzforschung, 55 (4): 417-425. https://doi.org/10.1515/HF.2001.069

Rosen H. N., 1978. The Influence of External Resistance on Moisture Adsorption Rates in Wood. Wood and Fiber Science, 10 (3): 218-228. https://wfs.swst.org/index.php/wfs/article/view/1228

Safou-Tchiama R., 2005. Caractérisation physico-chimique stabilité supramoléculaire et réactivité chimique de quelques essences tropicales. PhD thesis, Université Bordeaux 1, 175 p. https://theses.fr/2005BOR13095

Siau J. F., 1984. Steady-State Moisture Movement. In: Transport Processes in Wood. Springer Series in Wood Science, vol 2. Springer, 151-174. https://doi.org/10.1007/978-3-642-69213-0_6

Siau J. F., Avramidis S., 1996. The surface emission coefficient of wood. Wood and Fiber Science, 28 (2): 178-185. https://wfs.swst.org/index.php/wfs/article/view/1538

Simo-Tagne M., Rémond R., Rogaume Y., Zoulalian A., Bonoma B., 2016. Sorption behavior of four tropical woods using a dynamic vapor sorption standard analysis system. Maderas, Ciencia y Tecnologia, 18 (3): 403-412. https://doi.org/10.4067/S0718-221X2016005000036

Simpson W., 1973. Predicting equilibrium moisture content of wood by mathematical models. Wood and Fiber, 5 (1): 41-49. https://wfs.swst.org/index.php/wfs/article/view/740

Stamm A. J., 1959. Bound-water diffusion into wood in the fiber direction. Forest Products Journal, 9: 27-32. https://eurekamag.com/research/013/972/013972514.php

Storn R., Price K., 1997. Differential evolution – A simple and efficient heuristic for global optimization over continuous spaces. Journal of global optimization, 11: 341-359. https://doi.org/10.1023/A:1008202821328

Thybring E. E., Fredriksson M., Zelinka S. L., Glass S. V., 2022. Water in Wood: A Review of Current Understanding and Knowledge Gaps. Forests, 13 (12): 2051. https://doi.org/10.3390/f13122051

Varnier M., 2019. Comportement thermo-hygro-mécanique différé des feuillus : des sciences du bois à l'ingénierie. Thèse de doctorat, University of Limoges, HAL, Id: tel-02303304. https://theses.hal.science/tel-02303304v1/file/2019LIMO0035.pdf

Varnier M., Sauvat N., Ulmet L., Montero C., Dubois F., Gril J., 2020. Influence of temperature in a mass transfer simulation: application to wood. Wood Science and Technology, 54 (4): 943-962. https://doi.org/10.1007/s00226-020-01197-y

Yamamoto K., Hong L. T., 1994. A laboratory method for predicting the durability of tropical hardwoods. Japan Agricultural Research Quarterly (JARQ), 28 (4): 268-275. https://www.jircas.go.jp/sites/default/files/publication/jarq/28-4-268-275_0.pdf

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Exploring the potential of Near Infrared Hyperspectral Imaging and chemometrics to discriminate soil seed bank of two central African timber species: *Erythrophleum suaveolens* (Guill. & Perr.) Brenan and *Erythrophleum ivorense* A. Chev.

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Photo 1.
Near-infrared (NIR) hyperspectral imaging system
(courtesy of the Walloon Agricultural Research Center, Belgium).
Photo N. Kayoka Mukendi.

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RÉSUMÉ

Exploration du potentiel de l'imagerie hyperspectrale proche infrarouge et de la chimiométrie pour discriminer la banque de graines du sol de deux espèces de bois d'Afrique centrale : *Erythrophleum suaveolens* (Guill. & Perr.) Brenan et *Erythrophleum ivorense* A. Chev.

Les graines contenues dans la banque du sol peuvent être trop petites pour être quantifiées visuellement. Les espèces de bois concernées sont généralement identifiées lors d'essais de germination en pépinière, ce qui prend du temps. Cette étude explore une nouvelle approche fondée sur l'imagerie hyperspectrale dans le proche infrarouge (NIR-HSI) couplée à des outils chimiométriques. Elle se concentre sur la banque de graines du sol des forêts denses humides d'Afrique centrale, qui est encore méconnue. Nous avons utilisé quatre-vingt-trois graines de deux espèces sœurs, *Erythrophleum suaveolens* (Guill. & Perr.) Brenan et *Erythrophleum ivorense* A. Chev., collectées dans le sol forestier (profondeur entre 0 et 10 cm) au Gabon, au Cameroun et au Congo. À l'aide d'analyses en composantes principales et d'analyses discriminantes par moindres carrés partiels, nous avons étudié la capacité de l'imagerie hyperspectrale proche infrarouge à identifier les graines de deux espèces. La méthode est rapide, non-destructive et offre de nouvelles perspectives pour l'étude de la banque de graines des sols forestiers.

Mots-clés : banque de graines, espèces de bois, imagerie hyperspectrale proche infrarouge, chimiométrie, identification, discrimination.

ABSTRACT

Exploring the potential of Near Infrared Hyperspectral Imaging and chemometrics to discriminate soil seed bank of two central African timber species: *Erythrophleum suaveolens* (Guill. & Perr.) Brenan and *Erythrophleum ivorense* A. Chev.

Seeds contained in the soil bank can be too small to quantify visually. Concerned timber species are usually identified after germination trials in the nursery, which is time-consuming. This study explores a new approach based on near infrared (NIR-HSI) hyperspectral imaging coupled with chemometric tools. It focuses on the soil seed bank of the central African moist forests, which is still unknown. We used eighty-three seeds of two sister species, *Erythrophleum suaveolens* (Guill. & Perr.) Brenan and *Erythrophleum ivorense* A. Chev., collected in the forest soil (between 0 and 10 cm in depth), in Gabon, Cameroon, and Congo. Applying principal component analysis and partial least squares discriminant analysis, we studied the capacity of near-infrared hyperspectral imaging to identify the seeds of the two timber species. This method is fast, non-destructive, and offers new prospects for studies of forest soil seed banks.

Keywords: soil seed bank, timber species, near-infrared hyperspectral imaging, chemometrics, identification, discrimination.

RESUMEN

Estudio del potencial de la imagen hiperespectral del infrarrojo cercano combinado con la quimiometría para diferenciar dos especies de árboles centroafricanos en la reserva de semillas del suelo: *Erythrophleum suaveolens* (Guill. & Perr.) Brenan, y *Erythrophleum ivorense* A. Chev.

Las semillas contenidas en la reserva del suelo pueden ser demasiado pequeñas para cuantificarlas visualmente. Habitualmente estas especies se identifican después de intentos de germinación en el vivero, lo que requiere tiempo. Este estudio explora un nuevo enfoque basado en la imagen hiperespectral del infrarrojo cercano (NIR-HSI) combinada con herramientas quimiométricas. Se centra en la reserva de semillas del suelo de los bosques húmedos de África, que todavía es poco conocida. Usamos 83 semillas de dos especies hermanas, *Erythrophleum suaveolens* (Guill. & Perr.) Brenan y *Erythrophleum ivorense* A. Chev., recogidas en la reserva de semillas del suelo (entre 0 y 10 cm de profundidad), en el Gabón, el Camerún y el Congo. Aplicando análisis de componentes principales y análisis discriminante de mínimos cuadrados parciales, estudiamos la capacidad de la imaginería hiperespectral del infrarrojo cercano para identificar las semillas de ambas especies. Este método es rápido, no destructivo y ofrece nuevas perspectivas para estudios de reservas de semillas en suelos forestales.

Palabras clave: reserva de semillas del suelo, especies de madera, imágenes hiperespectrales en el infrarrojo cercano, quimiometría, identificación, discriminación.

Introduction

The soil seed bank designates the stock of viable seeds in the soil (Lipoma et al. 2018). It is considered a significant compartment of the natural regeneration in both temperate and tropical forests (Roberts 1981; Sousa et al. 2017) and represents the memory of plant communities in an ecosystem (Plue et al. 2010; Skowronek et al. 2014). Studies dealing with the soil seed bank could provide information on the structure and functioning of the forest ecosystems (Odum 1969; Hille Ris Lambers et al. 2005). Until recently, most studies on the seed bank of tropical forests were carried out in Asia and America (Martins and Engel 2007; Shen et al. 2014; Sousa et al. 2017). Over the past decade, however, studies in Central Africa have increased in number (Daïnou et al. 2011; Douh et al. 2018a; Zebaze et al. 2021; Padonou et al. 2022; Douh et al. 2023). All of them have been carried out using conventional methods. In order to identify the species present in the soil seed bank, germination tests were performed (Daïnou et al. 2011; Sousa et al. 2017; Douh et al. 2018a). This method is time-consuming, and protocols may vary from one author to another (Plaza-Bonilla et al. 2014). Another difficulty comes from ascertaining the viability of non-germinated seeds at the end of the experiments, especially for the smallest dormant seeds, which are almost unobservable in the soil bank. Consequently, the use of other, more effective techniques would be desirable to avoid underestimation in the quantification of the soil seed bank.

In this context, the use of near-infrared (NIR) spectroscopy technology linked with a microscope (NIRM) to identify seeds present in the soil deserves to be investigated.

In the recent years, new methods based on NIR spectroscopy technology have been developed. Thus, NIR has been linked with a microscope to create the NIR microscopy (NIRM). This spectrometer instrument includes a classical NIR spectrometer coupled with an optical microscope in which the optics have been adapted to NIR radiation.

Near-infrared microscopes allow the spectra to be collected from an extremely small sample (typically, 50 µm × 50 µm or less, depending on the instrument and the configuration) (Yang et al. 2011).

Recent developments in NIR Focal Plane Array (FPA) technology offer a solution to this problem in the form of imaging spectroscopy, which combines the advantages of spectroscopic and microscopic methods, along with much faster sample analysis since the spectral data are acquired in parallel. A NIR hyperspectral imaging spectrometer (NIR-HSI) gathers spectral and spatial data simultaneously by recording sequential images of a pre-defined sample (Fernández Pierna et al. 2004).

For both classical NIR and NIR-HSI, the advantages include simplicity of data acquisition, low cost per analysis, rapid inspection, non-destructive method, and accuracy (Fernández Pierna et al. 2004, 2012; Dale et al. 2012). Nonetheless, in NIR spectroscopy systems, samples usually have to be ground at less than 1 mm. With NIR-HSI systems, sample preparation is not necessary. The samples can be scanned without any grinding and can be subsequently used for other purposes (e.g., for germination trials) (Roggo et al. 2005).

Also, with NIR techniques, one measure gives one average spectrum, while thousands of spectra can be obtained with NIR-HSI, giving a complete picture of the distribution of chemical compounds at the pixel level (Ben-Dor and Banin 1995; Fernández Pierna et al. 2009; Dale et al. 2013; Shahin et al. 2014). Considering the complexity of the spectrum, chemometrics (application of mathematical tools, in particular statistics, to obtain maximum information from chemical data) and multivariate statistical approaches are needed to progress in the exploitation of the data (Massart et al. 1998).

The NIR-HSI has been used to discriminate mung bean seeds into normal and hard groups (Phuangsombut et al. 2018). This technology has also been used to identify the authenticity of maize seed varieties (Cui et al. 2018).

NIR-HSI has been revealed as a promising tool in the discrimination and identification of the quality of cereal grains (Fernández Pierna et al. 2010; Vermeulen et al. 2017; Caporaso et al. 2018). However, to our knowledge, this technology has never been used to discriminate or quantify the seed bank of forest soils.

In this work, a complete procedure based on NIR-HSI coupled with chemometrics has been proposed in order to discriminate the soil seed bank of the two-sister species exhibiting relatively similar morphological characteristics, namely *Erythrophleum suaveolens* (Guill. & Perr.) Brenan and *Erythrophleum ivorense* A. Chev. (Gorel et al. 2015).

Material and Methods

Species study and sampling of the soil seed bank

Erythrophleum suaveolens and *E. ivorense* are two timber species belonging to the family of Leguminosae-Detarioideae, exploited in central Africa (commonly known as “Tali”). *Erythrophleum suaveolens* is found in semi-deciduous rain tropical forests, forest galleries, and dry forests, while *E. ivorense* is found in evergreen rain forests (Aubréville 1970; Duminil et al. 2010). Both species are parapatric, and their distinction in contact zones is challenging (Gorel et al. 2015; Duminil et al. 2016). They have dormant seeds, and they are found in the soil seed bank at densities reaching 0.15 to 8.55 seed/m² (Douh et al. 2018b).

In this study, seeds of *E. suaveolens* were collected in June 2015 in the forests of Northern Republic of the Congo (Loundoungou) within 4 km²-plots of the DynAfFor[1] project.

[1] *Dynamique des forêts d’Afrique centrale*, http://www.dynafac.org

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Figure 1.
Location of the collection sites of seeds in Cameroon (Ma'an), in Congo (Loundoungou) and in Gabon (Estuaire).

Seeds of *E. ivorense* were collected in June 2008 and 2015 in the forests of Ma'an community (Cameroon) and of Estuaire province (Gabon) (figure 1). Globally, 83 seeds were collected in the 0-10 cm layer of soil. Table I summarises the characteristics of the seed collection sites (Segalen 1967; Freycon 2014).

Reference numbers have been assigned to each seed (68 seeds of *E. suaveolens* and 15 seeds of *E. ivorense*). Seeds were kept at ambient temperature and humidity for 30 days until posterior analysis using NIR-HSI.

Near-infrared (NIR) hyperspectral imaging (HSI)

Near-infrared hyperspectral images were acquired with a system combining a NIR hyperspectral line scan instrument and a conveyor belt (BurgerMetrics SIA, Riga, Latvia; photo 1). The camera was a short-wave infrared camera XEVA CL 2.5 320 TE4 (SPECIM Ltd., Oulu, Finland), using an ImSpector N25E spectrograph that includes a cooled, temperature-stabilised mercury-cadmium-telluride detector (XENICS NV, Leuven, Belgium). The images were acquired

Table I.
Synthetic description of the collection sites of seeds of *Erythrophleum suaveolens* and *E. ivorense*

	Cameroon (Ma'an)	Congo (Loundoungou)	Gabon (Estuaire)
Geographical coordinates	02°21' N – 02°35' N 08°42' E – 09°42'E	02°18' N – 02°22'N 17°31' E – 17°34'E	0°23'N – 0°24' N 9°15' E – 9°27' E
Altitude (m)	600 – 800	410 – 460	800 – 1,000
Annual rainfall (mm/an)	2,800	1,686	2,831
Soil types	Ferralsols	Acrisols-Arenosols-Gleysols	Acrisols-Arenosols-Gleysols
Geomorphology	Sandy to sandy-clay	Alluvial deposits in the Cuvette central of the Congo	Shale sandstone-Shale limestone
Forest types	Evergreen	Semi-deciduous	Evergreen

in the wavelength range from 1,100 nm to 2,400 nm, with a 6.3-nm spectral resolution (i.e., 209 wavelengths), and a width of 320 pixels using the protocol described by Fernández Pierna et al. (2006, 2012) and Vermeulen et al. (2010). Thirty-two (32) scans per image have been averaged, and each pixel provides an absorbance spectrum at each pixel of the image.

The near-infrared spectra acquired on both faces of each seed (lower and upper) were extracted with HyperSee software (BurgerMetrics SIA, Riga, Latvia), and an average of 1,000 pixels/spectra per seed were selected (figure 2). The faulty spectra (from which no information can be extracted) were removed from all images.

Analyses and soil seed bank identification

The first step before chemometrics analysis is the building of a spectral library. This is done by selecting representative spectra (the average spectra) of each seed variety from each acquired image. Then, this spectral library was used to assess the capacity of the NIR-HSI to distinguish seeds of *E. suaveolens* and *E. ivorense*. Once the library has been built, different chemometric tools have been used, namely a non-supervised method, principal component analysis (PCA, Legendre and Gallagher 2001; Wise et al. 2006), and a supervised technique, partial least squares discriminant analysis (PLS-DA, Naganathan et al. 2008; Williams et al. 2009; McGoverin et al. 2011). The PCA was used as an exploratory method to investigate the possibility of distinguishing the seeds of the two species on basis of their spectra linked to the chemical differences of the seed's constituents (Janné et al. 2001; Dale et al. 2012; Fernández Pierna et al. 2012).

The PCA loadings obtained from the PCA were investigated to figure out which molecules were responsible for the separation. If any, the seeds of both species (Reeve et al. 1996; Silverstein et al. 2007; ASD Inc. 2005-2013).

Regarding PLS-DA, a first calibration model needs to be built before being validated to check its capacity for discriminating both seed species. For this, 50 and 11 seeds of *E. suaveolens* and *E. ivorense* (photos 2 and 3), respectively, were used for calibration and 18 and 4 seeds (respectively for *E. suaveolens* and *E. ivorense*) for validation (Dale et al. 2013). The accuracy of the PLS-DA classification model was determined in terms of sensitivity and specificity values.

Sensitivity, or true positive rate, is a statistical measure of how the classification model is able to recognise a sample belonging to a given class. And the specificity, or true negative rate, measures the ability of the model to reject all samples not belonging to that given class (Eylenbosch et al. 2017).

All the analyses were performed using the Matlab R2015a software (The MathWorks, Inc., Natick, MA, USA) and the computing environment R (R Core Team, 2013).

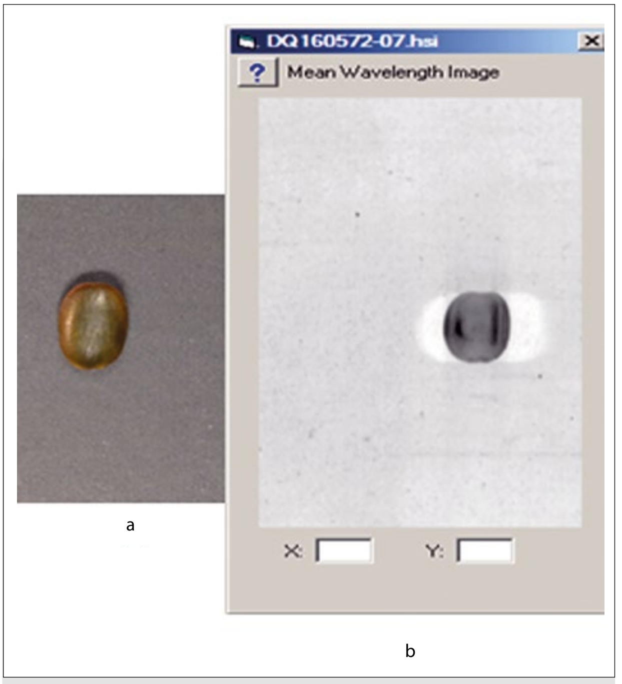

Figure 2.
a) Radial Basis Functions (RBF) image of a seed.
b) Near-infrared hyperspectral imaging (NIR-HSI) of the same seed.

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Results and discussion

Spectral signatures of *Erythrophleum suaveolens* and *E. ivorense* seeds

Figure 3 shows the spectra and the raw average spectra NIR of *E. suaveolens* and *E. ivorense* seeds obtained with NIR-HSI. The overall level of absorbance appears to be higher for *E. ivorense* seeds than for *E. suaveolens* seeds.

This trend shows that seeds of *E. suaveolens* would have significant light scattering, which would lead to a high level of reflection and therefore a relatively lower level of absorbance (Dale et al. 2012).

Discrimination of the soil seed bank of two timber species: *Erythrophleum suaveolens* and *E. ivorense*

Overall, a trend of discrimination between the two types of seeds is observed (figure 4). The first two axes of the PCA analysis display 95.01% of the explained variance (76.64% for the PC1 and 18.37% for the PC2). An observation of the PCA loadings (not shown) allowed refusing water absorption bands as responsible for this separation pattern. Using PLS-DA on the calibration set, a specificity and a sensibility of 100% were obtained. On the basis of the confusion matrix (table II), the validation of discrimination of *E. suaveolens* vs. *E. ivorense* displayed a sensibility of 100% and a specificity of 80%.

Consequently, these results confirm the ability of the PLS-DA classification method to discriminate the seeds of the two species.

Compared to *E. ivorense*, PCA loading reveals the presence of amino acids (group N-H) only in *E. suaveolens* seeds (wavelength, 1,500-1,600 nm) (Silverstein et al. 2007; ASD Inc. 2005-2013). Gorel et al. (2015) demonstrated that *E. suaveolens* had larger seeds than *E. ivorense*, and according to Duminil et al. (2016), *E. suaveolens* typically occupies drier climates than *E. ivorense*. Proteins are sources of nitrogen, carbon, and sulphur essential for the future nutritive needs of the embryo (Hacisalihoglu et al. 2010).

A larger amount of proteins in the seeds would ensure its vigour and probably a faster seedling development, which can be an advantage when the rainy season is shorter (Dumas and Rogowsky 2008; Noguero et al. 2011; D'Erfurth et al. 2012).

Conversely, the absence of proteins in the seeds of *E. ivorense* would prevent maintenance and renewal of the embryo tissues, and consequently, the seeds would have a prolonged dormancy compared to the seeds of *E. suaveolens*. This could be an advantage in evergreen forests, which are subject to less seasonality and lower light levels at ground level (Gond et al. 2013). Both *Erythrophleum* species are light-demanding and need a canopy gap to germinate (Duminil et al. 2016). We can therefore assume that this opening must be greater in evergreen forest than in semi-deciduous forest, which requires a longer waiting period in the soil.

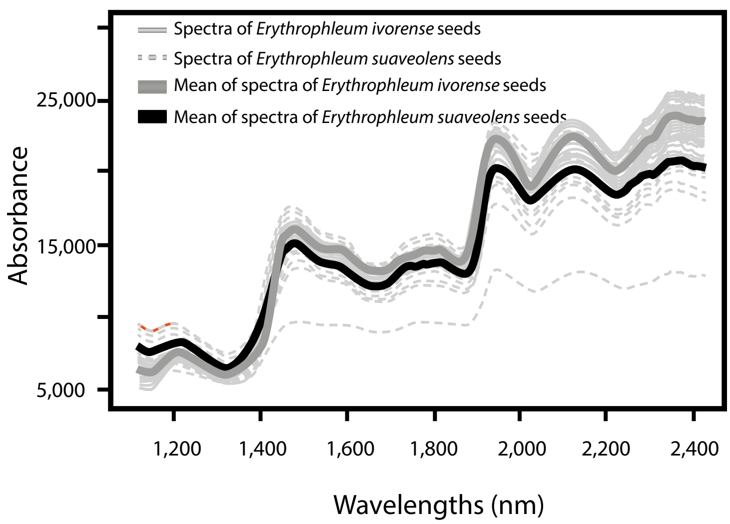

Figure 3.
The spectra and the raw average spectra of the 68 seeds of *Erythrophleum suaveolens* and 15 seeds of *E. ivorense*.

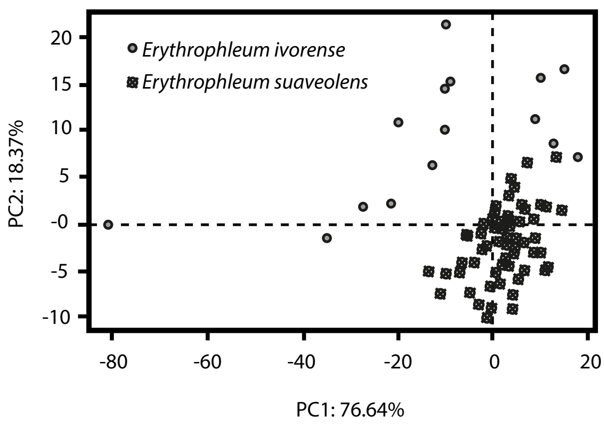

Figure 4.
Principal component analysis of seeds of *Erythrophleum suaveolens* and *E. ivorense*.

Photo 2.
Erythrophleum suaveolens seed.
Photo N. Kayoka Mukendi.

Photo 3.
Erythrophleum ivorense seed.
Photo N. Kayoka Mukendi.

Conclusion

This study demonstrated that near-infrared (NIR) hyperspectral imaging spectroscopy coupled with chemometrics is an efficient tool to discriminate the seeds of two sister tree species, here between *Erythrophleum suaveolens* (Guill. & Perr.) Brenan and *Erythrophleum ivorense* A. Chev. Seeds (photos 2 to 4), respectively collected in the forests of Loundoungou (Northern Republic of the Congo) for the first, and of Ma'an community (Southern Cameroon) and of Estuaire province (North-Western Gabon) for the second. Respective spectral signatures and the discrimination of the soil seed bank for the seed samples of both species were determined. The difference detected in seed protein content could explain the differences observed between the seeds of each species, but this result should be strengthened in future research using the Kjeldahl method (Kjeldahl 1883; Biancarosa et al. 2017; Sadaiah et al. 2018; Mæhre et al. 2018).

This exploratory research offers new perspectives in qualifying and quantifying the soil seed bank of forests.

But, in order to validate the approach, additional tests should be done on the smallest seeds found in the soil of the rainforests (Douh et al. 2018ab), such as *Musanga cecropioides*, *Nauclea diderrichii*, and *Macaranga* spp., without forgetting the species that are difficult to distinguish.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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Table II.
Discriminant Analysis (PLS-DA) confusion matrix of the two types of seeds.

Confusion Matrix				
Class	**TP**	**FP**	**TN**	**FN**
Erythrophleum ivorense	1.00000	0.00000	1.00000	0.00000
Erythrophleum suaveolens	1.00000	0.00000	1.00000	0.00000
Confusion table				
		Actual Class		
		Erythrophleum ivorense	*Erythrophleum suaveolens*	
Predicted as *E. ivorense*		15	0	
Predicted as *E. suaveolens*		0	68	
Key :				
Erythrophleum ivorense				
Erythrophleum suaveolens				
CV RESULTS				
Confusion Matrix (CV)				
Class	**TP**	**FP**	**TN**	**FN**
Erythrophleum ivorense	1.00000	0.00000	1.00000	0.00000
Erythrophleum suaveolens	1.00000	0.00000	1.00000	0.00000
Confusion Table (CV)				
		Actual Class		
		Erythrophleum ivorense	*Erythrophleum suaveolens*	
Predicted as *Erythrophleum ivorense*		15	0	
Predicted as *Erythrophleum suaveolens*		0	68	

TP = True Positive; FP = False Positive; TN = True Negative; FN = False Negative.

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Conditions of access to data

The data can be accessed using the Zenodo open digital repository link: https://doi.org/10.5281/zenodo.13908452

You are invited to cite this dataset and the article when using them and to inform the authors:

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Photo 4.
Tree trunk of *Erythrophleum* sp.
Photo J.-L Doucet.

References

Aubréville A., 1970. Légumineuses-Césalpinioidés (Leguminosae-Caesalpinioideae). Flore du Cameroun. Volume 9. Muséum National d'histoire Naturelle, Paris, France, 339 p.

Biancarosa I., Espe M., Bruckner C. G., Heesch S., Liland N., Waagbo R., *et al.*, 2017. Amino acid composition, protein content, and nitrogen-to-protein conversion factors of 21 seaweed species from Norwegian waters. Journal of Applied Phycology, 29: 1001-1009. https://doi.org/10.1007/s10811-016-0984-3

Ben-Dor E., Banin A., 1995. Near infrared analysis as a rapid method to simultaneously evaluate several soil properties. Soil Science Society of America Journal, 59: 364-372. https://doi.org/10.2136/sssaj1995.03615995005900020014x

Caporaso N., Whitworth M. B., Fisk I. D., 2018. Near-Infrared spectroscopy and hyperspectral imaging for non-destructive quality assessment of cereal grains. Applied Spectroscopy Reviews, 1-21. https://doi.org/10.1080/05704928.2018.1425214

Cui Y., Xu L., An D., Liu Z., Gu J., Li S., *et al.*, 2018. Identification of maize seed varieties based on near infrared reflectance spectroscopy and chemometrics. International Journal of Agricultural and Biological Engineering, 11: 177-183. https://doi.org/10.25165/j.ijabe.20181102.2815

Daïnou K., Bauduin A., Bourland N., Gillet J. F., Fétéké F., Doucet J.-L., 2011. Soil seed bank characteristics in Cameroonian rainforests and implications for post-logging forest recovery. Ecological Engineering, 37: 1499-1506. https://doi.org/10.1016/j.ecoleng.2011.05.004

Dale L. M., Thewis A., Boudry C., Rotar I., Dardenne P., Baeten V., *et al.*, 2013. Hyperspectral imaging applications in agriculture and agrofood product quality and safety control: a review. Applied Spectroscopy Reviews, 48: 142-159. https://doi.org/10.1080/05704928.2012.705800

Dale L. M., Thewis A., Rotar I., Fernández Piema J. A., Boudry C., Vidican R. M., *et al.*, 2012. Chemometric tools for NIRS and NIR hyperspectral imaging. Bulletin of Usavm Cluj-Napoca Agriculture, 69: 70-76. http://hdl.handle.net/2268/132855

D'Erfurth I., Le Signor C., Aubert G., Sanchez M., Vernoud V., Darchy B., *et al.*, 2012. A role for an endosperm-localized subtilase in the control of seed size in legumes. New Phytologist, 196: 738-751. https://doi.org/10.1111/j.1469-8137.2012.04296.x

Douh C., Daïnou K., Loumeto J. J., Moutsambote J.-M., Fayolle A., Tosso F., *et al.*, 2018a. Soil seed bank characteristics in two central African forest types and implications for forest restoration. Forest Ecology and Management, 409: 766-776. https://doi.org/10.1016/j.foreco.2017.12.012

Douh C., Gorel A. P., Daïnou K., Fonteyn D., Bustillo E., Obsomer L., *et al.*, 2018b. Banque de graines du sol et déterminants de la germination du tali, *Erythrophleum suaveolens* (Guill. & Perr.) Brenan. Bois et Forêts des Tropiques, 338 : 43-55. https://doi.org/10.19182/bft2018.338.a31681

Douh C., Mabengo B. C., Nzila J. D., Malonga Mbouchi L., Nsongola G., Loumeto J. J., *et al.*, 2023. Soil Seed Bank Characteristics in Congolese Rainforests and Implications for Post-Logging Plots Reforestation. Open Journal of Forestry, 13: 294-314. https://doi.org/10.4236/ojf.2023.133018

Dumas C., Rogowsky P., 2008. Fertilization and early seed formation. Académie des Sciences Institut de France, Comptes Rendus Biologies, 331: 715-725. https://doi.org/10.1016/j.crvi.2008.07.013

Duminil J., Daïnou K., Kombi Kaviriri D., Gillet P., Loo J., Doucet J.-L., *et al.*, 2016. Relationships between population density, fine-scale genetic structure, mating system and pollen dispersal in a timber tree from African rainforests. Heredity (Edinb), 116: 295-303. https://doi.org/10.1038/hdy.2015.101

Duminil J., Heuertz M., Doucet J.-L., Bourland N., Cruaud C., Gavory F., *et al.*, 2010. CpDNA-based species identification and phylogeography: application to African tropical tree species. Molecular Ecology, 19: 5469-5483. https://doi.org/10.1111/j.1365-294X.2010.04917.x

Eylenbosch D., Bodson B., Baeten V., Fernández Pierna J. A., 2017. NIR hyperspectral imaging spectroscopy and chemometrics for the discrimination of roots and crop residues extracted from soil samples. Journal of Chemometrics, 32: e2982. https://doi.org/10.1002/cem.2982

Fernández Pierna J. A., Vermeulen P., Amand O., Tossens A., Dardenne P., Baeten V., 2012. NIR Hyperspectral Imaging spectroscopy and chemometrics for the detection of undesirable substances in food and feed. Chemometrics and intelligent laboratory systems, 117: 233-239. https://doi.org/10.1016/j.chemolab.2012.02.004

Fernández Pierna J. A., Vermeulen P., Stilmant D., Dupuis B., Dardenne P., Baeten V., 2010. Characterisation of fonio millet by near infrared hyperspectral imaging, Proceedings of the 14th International Conference on Near Infrared Spectroscopy (ICNIRS): Breaking the Dawn. Bangkok, Thailand, 997-1002.

Fernández Pierna J. A., Baeten V., Dardenne P., Dubois J., Lewis E. N., Burger J., 2009. Spectroscopic Imaging. In: Comprehensive Chemometrics – 1st Edition. Brown S., Tauler R., Walczak B. (eds). Elsevier, 4: 173-196. https://doi.org/10.1016/B978-044452701-1.00004-1

Fernández Pierna J. A., Baeten V., Dardenne P., 2006. Screening of compound feeds using NIR hyperspectral data. Chemometrics and intelligent laboratory systems, 84: 114-118. https://doi.org/10.1016/j.chemolab.2006.03.012

Fernández Pierna J. A., Baeten V., Michotte Renier A., Cogdill R. P., Dardenne P., 2004. Combination of support vector machines (SVM) and near-infrared (NIR) imaging spectroscopy for the detection of meat and bone meal (MBM) in compound feeds. Journal of Chemometrics, 18: 341-349. https://doi.org/10.1002/cem.877

Freycon V., 2014. Caractérisation des sols de Loundoungou et de Mokabi (Congo). Rapport de mission DynAfFor, 2 au 24 avril 2014. CIRAD, Montpelier. https://agritrop.cirad.fr/573670/

Gond V., Fayolle A., Pennec A., Cornu G., Mayaux P., Camberlin P., et al., 2013. Vegetation structure and greenness in Central Africa from Modis multi-temporal data. Philosophical Transactions of the Royal Society: Biological Sciences, 368: 20120309. http://dx.doi.org/10.1098/rstb.2012.0309

Gorel A. P., Fayolle A., Doucet J.-L., 2015. Écologie et gestion des espèces multi-usages du genre *Erythrophleum* (Fabaceae-Caesapinioideae) en Afrique (synthèse bibliographique). Biotechnologie, Agronomie, Société et Environnement, 19 : 415-429. https://popups.uliege.be/1780-4507/index.php?id=12455

Hacisalihoglu G., Larbi B., Settles A., 2010. Near-Infrared reflectance spectroscopy predicts protein, starch, and seed weight in intact seeds of Common Bean (*Phaseolus vulgaris* L.). Journal of Agricultural and Food Chemistry, 58: 702-706. https://doi.org/10.1021/jf9019294

Hille Ris Lambers J., Clark J. S., Lavine M., 2005. Implications of seed banking for recruitment of southern Appalachian woody species. Ecology, 86: 85-95. https://doi.org/10.1890/03-0685

Janné K., Pettersen J., Lindberg N. O., Lundstedt T., 2001. Hierarchical principal component analysis (PCA) and projection to latent structure (PLS) technique on spectroscopic data as a data pre-treatment for calibration. Journal of Chemometrics, 15: 203-213. https://doi.org/10.1002/cem.677

Kjeldahl J., 1883. Neue Methode zur Bestimmung des Stickstoffs in organischen Körpern. Zeitschrift fur Anal Chemie, 22: 366-382. https://doi.org/10.1007/BF01338151

Legendre P., Gallagher E. D., 2001. Ecologically meaningful transformations for ordination of species data. Oecologia, 129: 271-280. https://doi.org/10.1007/s004420100716

Lipoma M. L., Funes G., Díaz S., 2018. Fire effects on the soil seed bank and post-fire resilience of a semi-arid shrubland in central Argentina. Austral Ecology, 43: 46-55. https://doi.org/10.1111/aec.12533

Martins A. M., Engel V. L., 2007. Soil seed banks in tropical forest fragments with different disturbance histories in south-eastern Brazil. Ecological Engineering, 31: 165-174. https://doi.org/10.1016/j.ecoleng.2007.05.008

Massart D. L., Vandeginste B. G. M., Buydens L. M. C., De Jong S., Lewi P. J., Smeyers-Verbeke J., 1998. Handbook of chemometrics and qualimetrics, Part A. NIR Publications, West Sussex, United Kingdom, 867 p. https://www.sciencedirect.com/bookseries/data-handling-in-science-and-technology/vol/20/part/PA

McGoverin C. M., Engelbrecht P., Geladi P., Manley M., 2011. Characterisation of nonviable whole barley, wheat and sorghum grains using near-infrared hyperspectral data and chemometrics. Analytical Bioanalytical. Chemistry, 401: 2283-2289. https://doi.org/10.1007/s00216-011-5291-x

Mæhre H. K., Dalheim L., Edvinsen G. K., Elvevoll E. O., Jensen I.-J., 2018. Protein determination-method matters. Foods, 7: 5. https://doi.org/10.3390/foods7010005

Naganathan G. K., Grimes L. M., Subbiah J., Calkins C. R., Samal A., Meyer G. E., 2008. Visible/near-infrared hyperspectral imaging for beef tenderness prediction. Computers and Electronics in Agriculture, 64: 225-233. https://doi.org/10.1016/j.compag.2008.05.020

Noguero M., Le Signor C., Verdier J., Aubert G., Udvardi M. K., Buitink J., *et al.*, 2011. Rôle de l'albumen dans le développement de la graine chez les légumineuses. *In* : Graine 2011 (p. S4). Colloque national du Réseau français de Biologie des Graines, Nantes, France, 27-28 octobre 2011. https://prodinra.inra.fr/record/48575

Odum E. P., 1969. The strategy of ecosystem development. Science, 164: 262-270.

Padonou E. A., Akakpo B. A., Tchigossou B., Djossa B., 2022. Methods of soil seed bank estimation: a literature review proposing further work in Africa. iForest, 15: 121-127. https://doi.org/10.3832/ifor3850-015

Phuangsombut K., Ma T., Inagaki T., Tsuchikawa S., Terdwongworakul A., 2018. Near-infrared hyperspectral imaging for classification of mung bean seeds. International Journal of Food Properties, 21: 799-807. https://doi.org/10.1080/10942912.2018.1476378

Plaza-Bonilla D., Álvaro-Fuentes J., Hansen N. C., Lampurlanés J., Cantero-Martínez C., 2014. Winter cereal root growth and aboveground-belowground biomass ratios as affected by site and tillage system in dryland Mediterranean conditions. Plant and soil, 374: 925-939. https://doi.org/10.1007/s11104-013-1926-3

Plue J., Verheyen K., Calster H. V., Marage D., Thompson K., Kalamees R., *et al.*, 2010. Seed banks of temperate deciduous forests during secondary succession. Journal of Vegetation Science, 21: 965-978. https://doi.org/10.1111/j.1654-1103.2010.01203.x

R Core Team, 2013. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.r-project.org/

Reeve A. S., Siegel D., Glaser P. H., 1996. Geochemical controls on peatland pore water from the Hudson Bay lowland: a multivariate statistical approach. Journal of Hydrology, 181: 285-304. https://doi.org/10.1016/0022-1694(95)02900-1

Roberts H. A., 1981. Seed banks in soils. In: Advances in Applied Biology. Coaker T. H. (ed.). Academic Press, 6: 1-55.

Roggo Y., Edmond A., Chalus P., Ulmschneider M., 2005. Infrared Hyperspectral Imaging for qualitative analysis of pharmaceutical solid forms. Analytica Chimica Acta, 535: 79-87. https://doi.org/10.1016/j.aca.2004.12.037

Sadaiah K., Veronica N., Nagendra V., Niharika G., Neeraja C. N., Surekha K., *et al.*, 2018. Methods of Protein Estimation and the Influence of Heat Stress on Rice Grain Protein. International Journal of Pure & Applied Bioscience, 6: 159-168. http://doi.org/10.18782/2320-7051.5733

Segalen P., 1967. Les sols et la géomorphologie du Cameroun. Cahier de l'ORSTOM, Série Pédologie, 5 (2) : 137-188.

Shahin M. A., Symons S. J., Hatcher D. W., 2014. Quantification of Mildew Damage in Soft Red Winter Wheat Based on Spectral Characteristics of Bulk Samples: A Comparison of Visible-Near-Infrared Imaging and Near-Infrared Spectroscopy. Food and Bioprocess Technology, 7: 224-234. https://doi.org/10.1007/s11947-012-1046-8

Shen Y. X., Liu W. L., Li Y. H., Guan H. L., 2014. Large sample area and size are needed for forest soil seed bank studies to ensure low discrepancy with standing vegetation. PLoS ONE, 9 (8): e105235. https://doi.org/10.1371/journal.pone.0105235

Silverstein R. M., Webster F. X., Kiemle D. J., 2007. Spectrometric identification of organic compounds. Seventh edition. State University of New York. College of Environmental Science & Forestry, 502 p. https://doi.org/10.1021/ed039p546

Skowronek S., Terwei A., Zerbe S., Mölder I., Annighöfer P., Kawaletz H., *et al.*, 2014. Regeneration potential of floodplain forests under the influence of non-native tree species: soil seed bank analysis in Northern Italy. Restoration Ecology, 22: 22-30. https://doi.org/10.1111/rec.12027

Sousa T. R., Costa F. R. C., Bentos T. V., Leal Filho N., Mesquita R. C. G., Ribeiro I. O., 2017. The effect of forest fragmentation on the soil seed bank of Central Amazonia. Forest Ecology and Management, 393: 105-112. https://doi.org/10.1016/j.foreco.2017.03.020

Vermeulen P., Ebene M. B., Orlando B., Fernández Pierna J. A., Baeten V., 2017. Online detection and quantification of particles of ergot bodies in cereal flour using near infrared hyperspectral imaging. Food Additives & Contaminants: Part A, 34 (8): 1312-1319. https://doi.org/10.1080/19440049.2017.1336798

Vermeulen P., Fernández Pierna J. A., Abbas O., Dardenne P., Baeten V., 2010. Authentication and traceability of agricultural and food products using vibrational spectroscopy. In: Applications of vibrational spectroscopy in food science. Li-Chan E.C.Y., Griffiths P.R., Chalmers J. M. (Eds.). United Kingdom, John Wiley & Sons, 609-630. https://doi.org/10.1002/0470027320.s8969

Williams P., Geladi P., Fox G., Manley M., 2009. Maize kernel hardness classification by Near Infrared (NIR) Hyperspectral Imaging and multivariate data analysis. Analytica Chimica Acta, 653: 121-130. https://doi.org/10.1016/j.aca.2009.09.005

Wise B. M., Shaver J. M., Gallagher N. B., Windig W., Bro R., Koch R. S., 2006. PLSJToolbox Version 4.0 for use with Matlab™. USA, Eigenvector Research Inc., 420 p.

Yang Z., Hana L., Fernandez Pierna J. A., Dardenne P., Baeten V., 2011. The potential of near infrared microscopy to detect, identify and quantify processed animal by-products. Journal of Near Infrared Spectroscopy, 19: 211-231. https://doi.org/10.1255/jnirs.935

Zebaze D., Fayolle A., Daïnou K., Libalah M., Droissart V., Sonké B., *et al.*, 2021. Land Use Has Little Influence on the Soil Seed Bank in a Central African Moist Forest. Biotropica, 54: 100-112. https://doi.org/10.1111/btp.13032

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Génomique écologique de l'exploitation de niche et de la performance individuelle chez les arbres forestiers tropicaux

Sylvain Schmitt

RÉSUMÉ

Partiellement inexpliquées et aux origines encore en débat, les forêts tropicales abritent la plus grande diversité d'espèces au monde. Même à l'échelle de l'hectare, elles abritent des genres diversifiés, avec des espèces d'arbres étroitement apparentées coexistant en sympatrie. En raison de contraintes phylogénétiques, on s'attend à ce que ces espèces possèdent des niches et des stratégies fonctionnelles similaires, ce qui interroge les mécanismes de leur coexistence locale. Ces espèces formeraient un complexe d'espèces, composé d'espèces morphologiquement similaires ou qui partagent une importante proportion de leur variabilité génétique en raison d'une ascendance commune récente ou d'hybridation, et qui résulterait d'une radiation écologique adaptative des espèces selon des gradients environnementaux. Malgré le rôle clé des complexes d'espèces dans l'écologie, la diversification et l'évolution des forêts néotropicales, les forces éco-évolutives à l'origine de leur diversité restent méconnues. Nous avons exploré la variabilité génétique intraspécifique, et mesuré son rôle sur la performance individuelle des arbres à travers leur croissance, tout en tenant compte des effets d'un environnement finement caractérisé aux niveaux abiotique et biotique. En combinant inventaires forestiers, topographie, traits fonctionnels foliaires, et des données de capture de gènes dans le dispositif de recherche permanent de Paracou, en Guyane française, nous avons utilisé la génomique des populations, les analyses d'associations environnementales et génomiques, et la modélisation bayésienne sur les complexes d'espèces *Symphonia* et *Eschweilera*. Nous avons montré que les complexes d'espèces d'arbres couvrent l'ensemble des gradients locaux de topographie et de compétition présents dans le site d'étude, alors que la plupart des espèces qui les composent présentent une différenciation de niche marquée le long de ces mêmes gradients. Plus précisément, dans ces complexes d'espèces, la diminution de la disponibilité en eau, le long de la topo séquence, a entraîné une modification des traits fonctionnels foliaires, depuis des stratégies d'acquisition à des stratégies conservatrices, tant entre les espèces qu'au sein de celles-ci. Les espèces de *Symphonia* sont génétiquement adaptées à la distribution de l'eau et des nutriments, coexistant localement en exploitant un large gradient d'habitats locaux. Inversement, les espèces d'*Eschweilera* sont différentiellement adaptées à la chimie du sol et évitent les habitats les plus humides et hydromorphes. Enfin, les génotypes individuels des espèces de *Symphonia* sont différentiellement adaptés pour se régénérer et croître en réponse à la fine dynamique spatio-temporelle des trouées forestières, avec des stratégies adaptatives de croissance divergentes le long des niches de succession. Par conséquent, la topographie et la dynamique des trouées forestières entraînent des adaptations spatio-temporelles à fine échelle des individus au sein et entre les espèces des complexes d'espèces *Symphonia* et *Eschweilera*. Ainsi, nous suggérons que les adaptations à la topographie et à la dynamique des trouées forestières pourraient favoriser la coexistence des individus au sein et entre les espèces d'arbres de forêts matures, appuyant le rôle primordial des individus au sein des espèces dans la diversité des forêts tropicales.

Mots-clés : coexistence des espèces, *Symphonia*, *Eschweilera*, complexe d'espèces, distribution des espèces, forêts tropicales, indice d'encombrement du voisinage, indice d'humidité topographique, niche écologique, Paracou, syngaméon, variabilité intraspécifique.

Ecological genomics of niche exploitation and individual performance in tropical forest trees

ABSTRACT

Tropical forests are home to the greatest diversity of species in the world. How this diversity evolved has not been fully explained, and its origins are still in debate. Even a single hectare comprises many different genera, with closely related tree species coexisting in sympatry. Due to phylogenetic constraints, they are expected to have similar niches and functional strategies, which raises questions about the mechanisms underlying their local coexistence. These tree species are thought to form a complex made up of species that are morphologically similar or have a significant proportion of genetic variability in common, due to recent common ancestry or hybridisation, and which could be the result of adaptive ecological radiation along environmental gradients. Despite the key role of species complexes in the ecology, diversification, and evolution of neotropical forests, the eco-evolutionary forces driving their diversity are still not well understood. We explored intraspecific genetic variability and measured its role in individual tree performance based on their growth, taking into account the effects of an environment that we characterised in detail at both abiotic and biotic levels. By combining forest inventories, topography, leaf functional traits, and gene capture data from the permanent research facility at Paracou in French Guiana, we applied population genomics, environmental and genomic association analyses, and Bayesian modelling to *Symphonia* and *Eschweilera* species complexes. We showed that these complexes cover all the local topography and competition gradients present in the study site, while most of the species making up each complex show marked niche differentiation along these same gradients. More specifically, the decrease in water availability along the topo sequence within these species complexes causes changes in leaf functional traits, from acquisition strategies to conservation strategies, both among and within species. *Symphonia* species are genetically adapted to the distribution of water and nutrients, coexisting locally by exploiting a broad gradient of local habitats. Conversely, *Eschweilera* species are differentially adapted to soil chemistry and avoid the wettest and most hydromorphic habitats. Finally, individual genotypes of Symphonia species are differentially adapted to regeneration and growth in response to the subtle spatio-temporal dynamics of forest gaps, with divergent adaptive growth strategies along successional niches. Therefore, forest gap topography and dynamics drive similarly subtle spatiotemporal adaptations of individuals within and among species of the *Symphonia* and *Eschweilera* species complexes. We therefore suggest that adaptations to forest gap topography and dynamics may favour the coexistence of individuals within and among mature forest tree species, supporting the central role of individuals of each species in tropical forest diversity.

Key words: coexistence of tree species, *Symphonia*, *Eschweilera*, species complex, distribution of species, tropical forests, neighbourhood crowding index, topographic wetness index, ecological niche, Paracou, syngamy, intraspecies variability.

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Genómica ecológica de la explotación de nicho y del rendimiento individual en los árboles forestales tropicales

RESUMEN

Las selvas tropicales albergan la mayor diversidad de especies del mundo, parcialmente inexplicada y cuyos orígenes todavía se debaten. Incluso a escala de hectárea, estas selvas albergan géneros diversificados, con especies de árboles estrechamente emparentadas coexistiendo en simpatría. A causa de las presiones filogenéticas, se espera que estas especies posean nichos y estrategias funcionales similares, lo que cuestiona los mecanismos de su coexistencia local. Estas especies formarían un complejo de especies, compuesto por especies morfológicamente similares o que comparten una importante proporción de su variabilidad genética en razón de una ascendencia común reciente o de la hibridación, que resultaría de una exclusión ecológica adaptativa de las especies según los gradientes medioambientales. A pesar del rol clave de los complejos de especies en la ecología, la diversificación y la evolución de las selvas neotropicales, todavía se desconocen las fuerzas ecoevolutivas que originan su diversidad. Hemos explorado la variabilidad genética intraespecífica y medido su rol en el rendimiento individual de los árboles a través de su crecimiento, teniendo en cuenta los efectos de un medio ambiente finamente caracterizado en los niveles abiótico y biótico. Combinando inventarios forestales, topografía, rasgos funcionales foliares, y datos de captura de genes en el dispositivo de búsqueda permanente de Paracou, en la Guayana Francesa, utilizamos la genómica de las poblaciones; los análisis de asociaciones medioambientales y genómicas, y la modelización bayesiana en los complejos de especies *Symphonia* y *Eschweilera*. Demostramos que los complejos de especies de árboles cubren el conjunto de los gradientes locales de topografía y de competencia presentes en el lugar de estudio, mientras la mayor parte de las especies que los componen presentan una diferenciación de nicho destacada a lo largo de estos mismos gradientes. Más concretamente, en estos complejos de especies, la disminución de la disponibilidad de agua, a lo largo de la toposecuencia, ha comportado una modificación de los rasgos funcionales foliares, desde las estrategias de adquisición hasta las estrategias conservadoras, tanto entre las especies como en el seno de las mismas. Las especies de *Symphonia* están genéticamente adaptadas a la distribución del agua y de los nutrientes, y coexisten localmente explotando un amplio gradiente de hábitats locales. Inversamente, las especies de *Eschweilera* están diferencialmente adaptadas a la química del suelo y evitan los hábitats más húmedos e hidromorfos. Finalmente, los genotipos individuales de las especies de *Symphonia* están diferencialmente adaptados para regenerarse y crecer en respuesta a la fina dinámica espaciotemporal de las brechas forestales, con estrategias adaptativas de crecimiento divergentes a lo largo de los nichos de sucesión. En consecuencia, la topografía y la dinámica de las brechas forestales comportan adaptaciones espaciotemporales en escala fina de los individuos en el seno y entre las especies de los complejos de especies *Symphonia* y *Eschweilera*. Así, sugerimos que las adaptaciones a la topografía y a la dinámica de las brechas forestales podrían favorecer la coexistencia de individuos en el seno y entre las especies de árboles de bosques maduros, apoyando el rol primordial de los individuos en el seno de las especies en la diversidad de las selvas tropicales.

Palabras clave: coexistencia de especies, *Symphonia, Eschweilera*, complejo de especies, distribución de las especies, selvas tropicales, índice de sobrecarga de vecindad, índice de humedad topográfica, nicho ecológico, Paracou, Syngaméon, variabilidad intraespecífica.

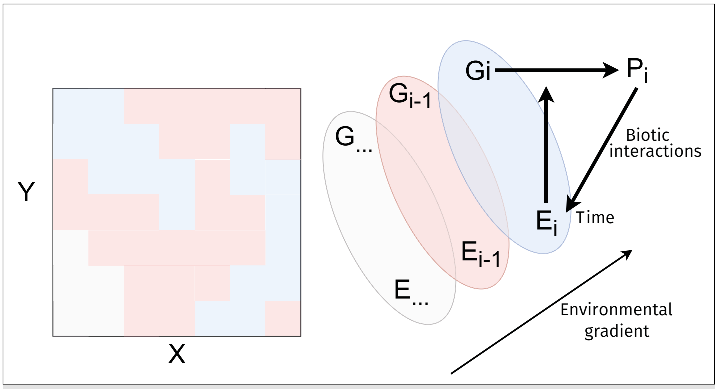

Figure 1. Adaptations micro géographiques entre espèces sympatriques au sein d'un complexe d'espèces. Différentes espèces génétiques G se développent en sympatrie dans des habitats spécifiques E le long d'un gradient environnemental. L'interaction entre l'environnement local Ei et le génotype Gi aboutit au phénotype Pi. Le phénotype Pi rétroagit sur son environnement local par le biais d'interactions biotiques. Les variations temporelles de l'environnement influencent le phénotype du génotype établi.
Figure 1. Microgeographic adaptations between sympatric species within a species complex. Different genetic species G develop in sympatry in specific habitats E along an environmental gradient. The interaction between the local environment Ei and the genotype Gi results in the phenotype Pi. The Pi phenotype retroacts on its local environment through biotic interactions. Temporal variations in the environment influence the phenotype of the established genotype.
Figura 1. Adaptaciones microgeográficas entre especies simpátricas en el seno de un complejo de especies. Diferentes especies genéticas G se desarrollan en simpatría en los hábitats específicos E a lo largo de un gradiente medioambiental. La interacción entre el medio ambiente local Ei y el genotipo Gi genera el fenotipo Pi. El fenotipo Pi retroactúa sobre su medio ambiente local por medio de interacciones bióticas. Las variaciones temporales del medio ambiente influyen en el fenotipo del genotipo establecido.

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List of the published references

Schmitt S., Trueba S., Coste S., Ducouret É., Tysklind N., Heuertz M., Bonal D., Burban B., Hérault B., Derroire G., 2022. Seasonal variation of leaf thickness: An overlooked component of functional trait variability. Plant Biology, 24: 458-463. https://doi.org/10.1111/plb.13395
Schmitt S., Tysklind N., Heuertz M., Hérault B., 2022. Selection in space and time: Individual tree growth is adapted to tropical forest gap dynamics. From the Cover, Molecular Ecology, [in press]. https://doi.org/10.1111/mec.16392
Schmitt S., Tysklind N., Hérault B., Heuertz M., 2021. Topography drives microgeographic adaptations of closely related species in two tropical tree species complexes. Molecular Ecology, 30: 5080-5093. https://doi.org/10.1111/mec.16116
Schmitt S., Tysklind N., Derroire G., Heuertz M., Hérault B., 2021. Topography shapes the local coexistence of tree species within species complexes of Neotropical forests. Oecologia, 196: 389-398. https://doi.org/10.1007/s00442-021-04939-2
S. Schmitt, B. Hérault, É. Ducouret, A. Baranger, N. Tysklind, M. Heuertz, et al., 2020. Topography consistently drives intra- and inter-specific leaf trait variation within tree species complexes in a Neotropical forest. Oikos, 196: 1521-1530. https://doi.org/10.1111/oik.07488
Kattge J., Bönisch G., ..., S. Schmitt, *et al.*, 2020. TRY plant trait database–enhanced coverage and open access. Global Change Biology, 26: 119-188. https://doi.org/10.1111/gcb.14904

TREES, FORESTS & CLIMATE

29th Conference of the Parties to the landmark UN Framework Convention on Climate Change (UNFCCC)

BAKU, AZERBAIJAN

11th-22nd November 2024

As the 29th Conference of the Parties to the landmark UN Framework Convention on Climate Change (UNFCCC) whirs into gear, the role of forests and trees in mitigating both anthropogenic climate change and its most disastrous impacts – and helping people and ecosystems adapt to the changes that are already happening – is more critical than ever.

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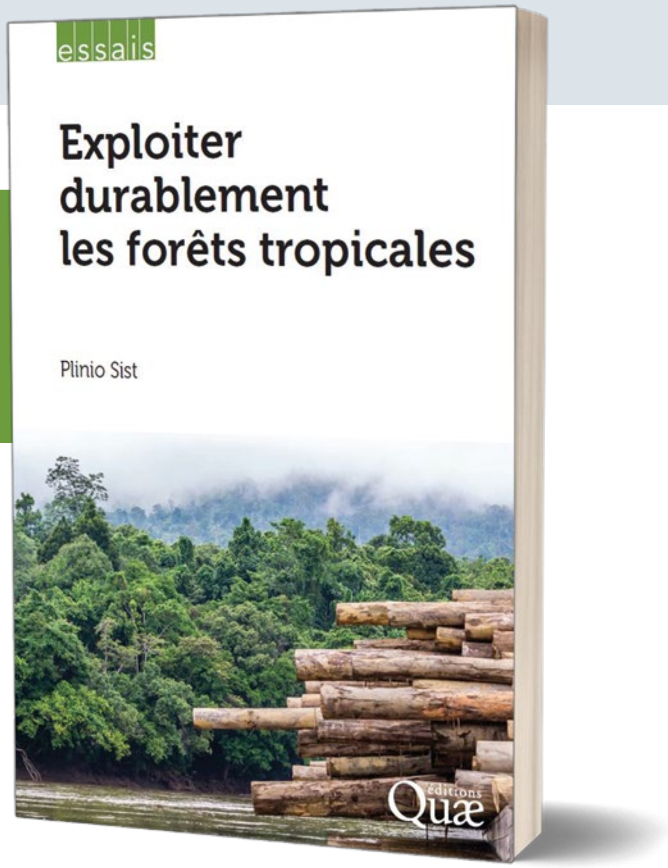

Au cours des trente dernières années, plus de quatre cents millions d'hectares de forêts tropicales ont été détruits. À cette déforestation s'ajoute la dégradation forestière qui dans certaines régions du monde, comme l'Amazonie, affecte autant de surface que le déboisement. Préserver et conserver les forêts tropicales devient donc aujourd'hui une priorité pour la survie de l'humanité.

Une première méthode consiste à sanctuariser les forêts en créant des aires protégées, limitant ainsi l'exploitation de leurs ressources par les humains. La seconde repose sur une exploitation raisonnée au bénéfice des populations locales et de la société en général. Les forestiers privilégient cette méthode avec l'idée qu'une forêt valorisée générant des biens et des services aux populations, à l'État et à la société sera une forêt protégée et conservée.

Cependant, la réalité sur le terrain continue de contredire ce principe. L'exploitation illégale, encore très répandue dans de nombreux pays tropicaux, engendre d'importants dégâts aux peuplements forestiers, et compromet leur capacité à se régénérer et à résister aux effets du changement climatique. L'exploitation du bois d'œuvre est ainsi accusée de tous les maux et est très souvent considérée comme la principale source de déforestation.

Cet essai vise non pas à réhabiliter l'exploitation forestière, mais à présenter de façon objective, factuelle et accessible aux personnes non spécialistes des forêts tropicales les effets environnementaux de l'exploitation du bois d'œuvre. Il révèle les différentes voies possibles pour que cette exploitation devienne un véritable outil de conservation des forêts tropicales humides.

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L'auteur, Plinio Sist, est le directeur de l'unité de recherche Forêts et sociétés du Cirad. Ses recherches, réalisées essentiellement en Amérique latine et en Asie du Sud-Est, portent sur l'écologie et la gestion des forêts tropicales humides.

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