DESIGN METHODOLOGY FOR THE IDENTIFICATION AND SCALING OF NATURE-BASED SOLUTION FOR CARBON DIOXYDE CAPTURE AND STORAGE

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ABSTRACT

This article addresses the urgent need to combat climate change by exploring Nature-based Solutions (NbS) for carbon capture, utilization, and storage (CCUS). The existing CCUS technologies face challenges of maturity, energy intensity, and high costs. To answer this challenge, this work proposes a new design methodology to facilitate the identification, evaluation and scaling of NbS for CCUS in a systematic and impactful manner.

The proposed method involves analyzing a problem, identifying the required function, and using keywords to guide the research. Through iteration, the array of potential solutions expands, providing diverse options with various biological functions. Then, the focus shifts to narrowing down the most promising solutions to reduce the number of potential NbS. Common functions are identified, solutions are organized by domain, and priorities are set based on ability, effectiveness, and cost. Finally, scalability insights, as well as the enablers and barriers, are identified to design a roadmap for scaling the NbS.

Applied to the case study of CCUS, 68 NbS emerged, including bivalve, and carbonic anhydrase for example. The method then narrowed down the research to five top solutions: cactus, mycorrhizal fungi, microalgae, cobalt oxide and rocks (basalt, olivine) for enhanced weathering. This approach facilitates the efficient identification of promising NbS. Subsequently, scalability insights and a roadmap were developed, using the example of the Opuntia ficus-indica cactus, which was one of the five NbS selected.

1 INTRODUCTION

"Climate change: a threat to human wellbeing and health of the planet. Taking action now can secure our future" (IPCC (Intergovernmental Panel on Climate Change), 2022). Climate change caused by human activities is leading to severe and widespread disruptions in nature, affecting billions of people globally. Despite attempts to mitigate risks, the adverse effects are disproportionately affecting those least equipped to adapt, according to the latest report from the Intergovernmental Panel on Climate Change. To mitigate climate change and its consequences, it's imperative that we reduce our anthropogenic emissions. Even if companies manage to drastically cut emissions by 2050, there will still be residual emissions remaining in their carbon footprint. According to Jones et al. (2023), carbon dioxide accounts for almost 75% of the greenhouse gas emissions in 2020, underscoring the importance of carbon capture. Achieving carbon neutrality necessitates offsetting these residual emissions, thereby

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emphasizing the significance of carbon removal. But, how can we remove almost 8 Gt of CO_2 by 2050 as the IAE (International Energy Agency) suggests when in 2024 we only capture 46 Mt or 0.6% of the objective? What technologies do we have to adopt? How can we scale them? This is going to be one of the challenge of our century and we are at the premises of it.

2 BACKGROUNG

The IEA evaluates in its Net Zero Emissions by 2050 scenario that 7,6 Gt CO_2 will have to be captured and stored annually after 2050 while in 2018, 51.2 gigatons of CO_2 equivalent were emitted (M. Crippa et al., 2021). CCUS appear then as another necessary step to reach carbon neutrality even though we should not rely on them. The main efforts will still be in reducing our emissions in the first place through more efficient systems, a massive electrification (a decarbonized one of course) and sobriety to mention a few.

Two type of technological capture exist:

- Capture the CO_2 from the atmosphere: CO_2 is captured directly from the atmosphere.
- Capture the CO_2 from point source: Following or before the combustion of fossil fuels or waste, the outgoing fumes are filtered, and CO_2 is captured.

There are now around 40 commercial capture facilities in operation globally, with a total annual capture capacity of more than 45 Mt CO_2 (IEA).

We saw that technologies do exist to capture and store carbon dioxide. Yet, there are not mature enough, expensive and not easy to scale up considering the investments required. Conversely, NBS (Nature-based Solution) do not need such investment. The European Commission, in the Research and Innovation policy agenda on Nature-based Solutions and Renaturing Cities, defines NBS as *"solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions."* (European Commission, 2015). With the potential to mitigate climate change, halt biodiversity loss, and promote human well-being (Chausson et al. 2020), NBS can contribute by, for instance, reducing anthropogenic carbon emissions (Pan et al. 2023).

However, despite our literature research efforts, we have not been able to find a specific framework or approach to effectively guide the identification and scaling of NbS for CCUS. This gap in methodology represents a significant challenge in the field, hindering the broader adoption and implementation of NbS as viable strategies for addressing climate change issues. As such, there is a critical need for further research and development in this area and we propose a new design methodology to facilitate the identification, evaluation, and scaling of NbS in a systematic and impactful manner. We will apply this methodology to the specific case of CCUS.

3 METHODOLOGY

NbS open an entire range of solutions to tackle climate change and sustainability challenges including reducing anthropogenic carbon emissions (Sarkki *et al.*, 2024). Thus mainstreaming NbS to address those challenges and in our case carbon removal is essential. The main objective of this methodology is to make NbS approach accessible to everyone. Thus, deep knowledge in biology or investments in tools are not necessary. The second objective is to identify as much potential NbS as possible and thus make sure to cover as much possibilities as possible. The following methodology strives to be systematic. These different methods of identification and scaling demonstrates a range of possibilities

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to scale NbS. Figure 1 shows our methodology, from the identification of a model to the scaling in four stages:

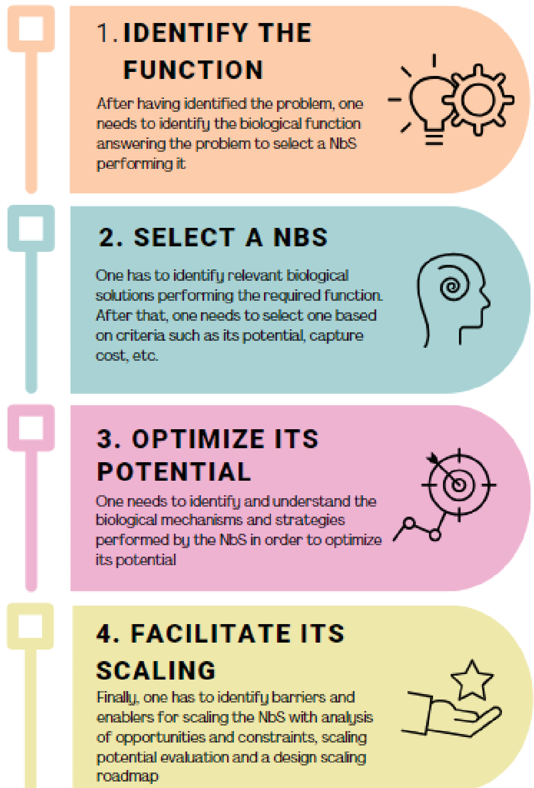

Figure 1: Scaling methodology

The following sub-sections provide detailed descriptions of each of the four stages.

3.1 Stage 1: Identify the function.

First, we need to identify the problem and then the function answering to the problem. Thus, we need to identify the problem and a general problematic. The objective there is to identify resolution spaces, which will help our research later. Next, we will find key words and functions relative to our problematic. Then, we need to identify the biological functions that could deal with our problematic. To do so, we will use the biomimicry taxonomy (Asknature, 2008) created by the Biomimicry Institute. It makes an inventory of all the functions a living organism can perform. We can identify the most relevant ones, but we just need 2-3 functions here, just like the key words.

Then, we identify the required biological function corresponding to the one previously identified.

3.2 Stage 2: Select a NbS

In this stage, the objective is to identify a NbS that could answer our problem. We will identify potential NbS performing the function desired. For this step, we used open-source databases such as Asknature, Wiley open library, INPN, BioOne or Science Direct. When using Asknature, we can filter organism by the functions previously identified. We also conducted searches for models by entering key words in the search bar. Then, we selected the organisms that could be transpose into our subject. After identifying a relevant biological model, we proceeded to identify the principles and structure utilized by it.

It can be noted that the model may perform multiple functions. In such cases, if one of its functions appears relevant to the current problem, we can explore other biological examples with the same function and proceed with the method. However, if the function seems less relevant, we can categorize

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organisms fulfilling that function as carriers of diversification. These are less studied organisms, more distant from the technical context, but they represent the biological diversity surrounding the model (Graeff, 2020). Finally, while understanding the principles at play in biological models, we can identify relevant biological terms, enabling us to return to the search of solutions based on those. This iterative process enhances the relevance and number of models through the discovery of new functions and relevant biological terms, leading to new conceptual associations and keywords.

After identifying all these solutions, we need to select a NbS. To do so, we reduce this previous list in order to analyse them deeper, understanding how they work and considering how we could scale them. First, we gather the solutions by biological mechanisms (store, catalyse, capture, break down). Then, we divide them according to their kingdom (animal, vegetal, bacteria, fungi, non-living) and kept the ones with the best potential based on criteria such as price ($/t$CO_2$), rate, efficiency, maturity, potential, valorisation.

3.3 Stage 3: Optimize its potential.

Then, we can optimize its potential. To do so, it is essential to first understand how it performs the function of interest and identify the factors that influence its performance. This understanding allows us to determine the best conditions for the model to fulfil its potential.

Understanding the model's performance involves evaluating how it executes its specific function through a detailed examination of its processes and outputs. Identifying the factors that influence the model's performance includes studying the effects of external conditions like temperature, humidity, and light. It also involves analysing how different input variables affect the model's output to pinpoint key factors that influence performance. Experimenting with various operational settings helps in determining the optimal configuration for the model.

Optimizing the model's conditions can be achieved by adjusting its parameters to enhance performance, employing techniques such as grid search, random search, and Bayesian optimization. Creating controlled environments reduces variability and ensures consistent performance. Implementing feedback mechanisms allows for continuous monitoring and real-time adjustments.

By systematically analysing performance, understanding influencing factors, optimizing conditions, and considering genetic enhancements, we can maximize the model's potential and ensure it operates at its highest capability.

3.4 Stage 4: Facilitate its scaling.

Finally, after we know how to optimize the potential, we need to facilitate the scaling of the solution. Thus, we need to identify the key features of the solution, to identify the barriers and enablers to scaling, to conduct analysis of the geophysical opportunities and constraints and finally, to design a scaling roadmap.

First, we identify and understand the essential components and performance metrics of the optimized solution. We assess its adaptability to different environments to ensure effectiveness at larger scales. Next, we identify barriers such as technical challenges and resource limitations, as well as enablers like available technology and supportive policies. Then, we conduct a thorough analysis of these factors to address them early. Then, we analyze the geophysical context to find opportunities and constraints and identify regions with favorable conditions and resources and recognize areas where challenges might arise. Finally, we design a comprehensive scaling roadmap and develop a strategic plan with short-term and long-term goals, milestones, and timelines. We engage stakeholders, allocate necessary resources, and implement a monitoring and evaluation framework to track progress and measure impact.

By systematically addressing these steps, we can successfully scale the solution, ensuring it maintains effectiveness and adapts to different contexts, ultimately achieving broader impact and sustainability.

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4 RESULTS

We will implement the methodology outlined in part 3 to the specific case of CCUS. Each of the four stages is detailed in the following sub-sections.

4.1 Results of the identification of relevant functions

As mentioned in the previous chapter, we have first identified problem: How to remove carbon dioxide from the atmosphere. Then, to help our research of NbS, we have found keywords such as “carbon capture”, “carbon removal”, “carbon storage”. We have also identified the most relevant functions considering our keywords and the problematic. As seen in the previous chapter, we used the biomimicry taxonomy to do so. From all the functions identified by the biomimicry institute, who developed this taxonomy, we have considered the following functions “Get, store or distribute resources, Capture, absorb or filter, Gases” and “Get, store or distribute resources, Store, Gases” as the most relevant ones.

4.2 Results of the selection of the relevant biological solutions

Then, by following this methodology, 68 solutions were found. Half are vegetals, 13 animals, 11 bacteria, 8 non living solutions and 3 fungi. 39 were found with Asknature. Asknature is the most user friendly but if we had only used it, we would have missed almost half of the solutions. For example, a search with the term “carbon dioxide”, revealed that cacti sequester atmospheric carbon dioxide by converting it to oxalate and to solid calcium carbonate preventing cacti to release carbon dioxide in the atmosphere when they die. Cacti demonstrated an interesting function of "capturing, absorbing, or filtering chemical entities." Further exploration led us to identify "green algae" as a potential solution among other organisms with this function.

Thus, searching on other platforms although less user friendly and with relevant information harder to find is essential if we do not want to miss potential solutions. This methodology allows us to find a lot of solutions but does not guarantee that you will find all of them. This step has been carried out manually, but a computer program comprising instructions adapted to execute the steps of the biomimetic treatment process has yet to be developed.

After identifying all the models that could address our issue, we reduced the list of biological solutions. From 68, we kept 5 solutions. Thus, we kept the micro-algae, the silicate rocks with the principle of enhanced weathering, the mycorrhizal fungi, the cobalt oxide and the Opuntia ficus-indica cactus.

We are now going to do a deeper analysis of the Opuntia ficus-indica cactus. We estimated cacti as a solution with a lot of potential because they can store carbon dioxide through mineralization and represent less risk of fires and permanent storage, contrary to tropical trees for instance.

4.3 Results of the optimization of its potential

We are here at the third stage *“Optimize its potential”*. We need to comprehend the mechanisms and biological strategies of cacti, explore their influences with quantitative results, and identify potential areas for improvement.

Cacti grow in arid and semi-arid areas. Arid and semi-arid regions cover about 30% of the world’s continental surface. They occupy a territorial area of approximately 66.7 million km² of the globe (Alves *et al.*, 2022).

The cactus captures carbon dioxide through its cladodes and stomata, acting like pores, using the photosynthesis mechanism. The cactus exhibits Crassulacean Acid Metabolism (CAM), with nocturnal stomata opening and CO_2 uptake occurring from dusk to dawn (Nefazoui *et al.*, 2014). This unique metabolism reduces water loss during the day, making it more efficient, especially in high temperatures. The cactus sequesters atmospheric carbon dioxide by converting it to oxalate and combining it with soil-derived calcium ions, leading to the formation of calcium oxalate, which turns into solid calcium carbonate after the cactus's death (Garvie, 2006). This process takes between 10 to 20 years. Calcium oxalate can constitute up to 85% of the dry organic material in some cacti (Garvie, 2006). Thus, instead

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of releasing CO_2 through the decomposition of the cactus, the carbon within it is converted into calcium oxalate, effectively sequestering it permanently in the soil.

On average, the Opuntia ficus-indica cactus captures and stores 23 tons of CO_2 per hectare per year (Andreu-Coll *et al.*, 2020).

External factors can influence the carbon capture potential such as:

- Temperature: Lethal cactus temperatures range from -10°C to 65°C (Nobel, 2002). The cactus exhibits 80% of its maximum carbon uptake between 6 and 20°C during the night (Inglese *et al.*, 2017).
- Rain/Irrigation: Cacti have low water demand, demonstrating water-use efficiencies three to six times higher than other crops. For carbon capture or in areas with less than 300mm/year average rainfall, cacti require additional irrigation (10mm/month) for optimum capture (Neto *et al.*, 2020).
- Fertilization: Nutrients like Nitrogen (N) stimulate cell division and promote new cladode growth. Phosphorus stimulates fruit production, and Potassium is also essential. The choice of fertilizer, whether chemical or natural, should consider its impact on soil and carbon intensity.
- Light: Net CO_2 uptake increases linearly with total daily Photosynthetic Photon Flux (PPF), and exposed stems have longer periods of CO_2 uptake with higher rates (Pimienta-Barrios *et al.*, 2000).

4.4 Results of the scaling strategies

After analyzing carbon removal potential, we must address the objectives and trade-offs of nature-based solutions (NbS), as well as the enablers and barriers to scaling. Approaches include scaling out, up, deep, and cross-cutting.

Scaling out involves identifying new pilot locations based on suitability and carbon sequestration potential, replicating successful strategies in different regions, and forming partnerships with local communities, agricultural agencies, and environmental organizations. As we move to scaling up, the focus shifts to analysing market opportunities for cactus-based products and the economic viability of carbon credits. This involves collaborating with government agencies for subsidies and support for large-scale cactus cultivation and promoting programs like the Green Morocco Plan. Additionally, scaling deep requires investing in research and development to understand cactus biology better and optimize carbon capture. This involves exploring innovative farming techniques, genetic enhancements, and sustainable practices. Lastly, cross-cutting approaches involve fostering collaboration between large-scale cactus farming programs in countries like Mexico and Morocco and creating platforms for knowledge exchange among farmers and cooperatives.

To implement these insights, identifying enablers and barriers is crucial. Financial gains from cactus valorization and carbon credits can provide additional income for farmers. Social benefits include building associations and local economies, especially in rural areas. Cactus farms offer potential for voluntary carbon credits for companies needing offsets. New policies should support the valorization chain through regulations and subsidies.

However, there are barriers to scaling. Developing cacti potential requires large areas. Using cacti for carbon capture is new, with a lack of knowledge about net CO_2 uptake by age. Financial investments are necessary if farmers want to turn cactus into biofuel or leather, requiring equipment and knowledge investments.

Now, we can establish a roadmap of scaling cactus:

1. Identification and selection of the NbS addressing the problematic

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2. Expert validation about the selected solution
3. Deep dive into the chosen solution (potential, influences, barriers, enablers, objectives and trade-offs analysis, scalability insights)
4. Implementation of a pilot project (optimize conditions for growth and carbon capture and monitor the project's success and challenges)
5. Iterative improvement of scaling (gather data and feedback from the pilot project and implement changes to enhance overall effectiveness)
6. Continuous monitoring and adaptation (adapt strategies based on changing conditions and new insights, ensure ongoing optimization for long-term sustainability)

Following this application case, it can be concluded that the methodology indeed facilitates the identification of relevant solutions. However, further experimentation is necessary to validate its effectiveness and generalizability. More extensive testing across various contexts and scenarios will help to confirm the robustness and versatility of the approach.

5 CONCLUSION

In this study, our objective was to explore Nature-based Solutions (NbS) for carbon dioxide removal and to develop methods for their scalability. We introduced an innovative approach to efficiently identify and scale relevant nature-based solutions tailored to a specific problem. By identifying key words and relevant functions, we initiated an initial search for biological models addressing our issue. Subsequently, through our research, we uncovered new relevant functions and keywords, expanding our array of solutions and consequently increasing the number of pertinent biological solutions. This iteration process allowed us to double the number of solutions. Then, to scale an NbS, we should optimize its potential and facilitate its deployment by identifying barriers and enablers. It involves conducting analyses of geophysical opportunities and constraints and, finally, designing a scaling roadmap. Finally, we should develop specific scaling strategies according to our NbS.
As a result, we have identified 68 NbS addressing our issue. Later, we narrowed the list of solutions down from 68 to 5 based on criteria such as the cost of capture, the rate and the potential. Finally, we presented various strategies for scaling these solutions and integrated them into a comprehensive systemic methodology.

However, our current methodology for scaling NbS has limitations, as experts and specialists should be more integrated and developed in the process of identification and selection. Moreover, a more thorough methodology, including the definition of criteria, to screen current NbS solutions and evaluate their potential for further improvement, would be of interest. At last, the step of identification and selection of NbS is still carried manually but deserves to be more rigorous or to be automated.

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