The Mangrove Still - A bio-inspired design approach to address soil degradation in arid seawater coastal areas

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Extended Abstract:
Land degradation and water scarcity are global challenges compromising food security; they especially affect the livelihood of poor people who heavily depend on agriculture. Millions of them live in arid and semi-arid seawater coastal areas. Bringing enough water in these areas, together with suitable land practices, could help regenerating the degraded soil and its productivity. To address this complex challenge a Biologically-Inspired Design approach, the Biomimicry Thinking, was applied.
Initially an investigation at system level was carried out. Coastal seawater ecosystems such as Mangroves and Salt Marshes manage were investigated and how water resources are managed. Looking at the development of the whole ecosystem, pioneer species such as *Avicennia* and *Salicornia*, which thrive in salty water, are the ones which start to build up the ecosystem creating conditions conducive for other species to come which will slowly enhance the soil texture and its microbiology and eventually have access to, store and distribute other water resources coming from rare rainfalls, air moisture and floods. Human approach to planning and design often considers desalination as *the only* solution to generate large amount of fresh water in arid coastal areas. To the contrary in pursuing an ecosystem approach where development and growth are interconnected and mutually regulating processes and the use of locally available resources is optimized, Nature seems considering desalination as a kick-starting process to activate other different strategies to access available water resources and generate healthy soil. To emulate this process, the solar still was selected as a "pioneer technological species". A functional analysis of several existing designs of the still was carried out and improvements were applied looking at how nature carries out similar functions. The design developed so far - named the **Mangrove Still** - embeds nature's design principles which optimize surface/volume ration, the capture of light and thermal regulation. Again, following natural principles of sustainability, the still is built with recyclable, re-usable and locally available materials. Furthermore, thanks to its particular lightness and modularity, several stills can be assembled in systems creating adaptable configurations (centralized and distributed) to provide water to the land or drinking water to people. After initial tests on a prototype, the Mangrove still shows efficiency comparable to current solar stills but it costs at least 5 times less. These features, differently from other existing solar stills, may allow to industrialize the production and assembling of the still generating sustainable business models viable also for poor people. The Mangrove Still aims at providing enough water to activate appropriate soil regeneration practices which will progressively enhance soil quality and land revegetation allowing regenerating land in coastal areas and build up sustainable communities the same way natural ecosystems develop and grow.
This paper wants also to promote the potentiality for sustainable innovation using living systems as source for inspiration. The sector of technologies for desalination (as the whole water management sector) could benefit from a Biologically-Inspired Design approach.

1. Introduction – the Biomimicry Thinking approach

This paper reports the initial results of a project undertaken by the authors (the team) to participate to the *Global Biomimicry Design Challenge* launched in October 2014 by the Biomimicry Institute (challenge.biomimicry.org). The general theme of the Challenge was the improvement of Food Systems. The Challenge had to be undertaken utilizing the Biologically-Inspired Design approach developed by the Institute named the *Biomimicry Thinking* approach. In a nut shell the approach foreseen sequential phases: *Scoping, Discovery, Creating and Evaluating*[i]. In the *Scoping* phase the challenge (i.e. the design problem) has to be framed and explored in its context and specific functions solving the challenge have to be determined. Once the functions solving the challenge are set, the question has to be turned into biological terms (How would Nature do this?). Answering this question allows entering into the *Discovery* phase which foresees the investigation into Nature to find living systems which are carrying out similar functions. Once identified, their strategies and mechanisms to carry out the functions are understood and described. The strategies and mechanisms identified are described in biological terms and therefore still maintain information from the biology which are not useful and can be misleading for engineers. Therefore these descriptions need to be "cleaned" from the biology context or "abstracted" into clear design principles. The *Creating* phase foresees the brainstorming process typical of other problem solving approaches where design concepts are developed and prototypes are set up and tested. The solutions identified are then subject to an evaluation process vis-`a-vis specific overarching natural design principles (called the *Life's Principles*) which have been identified as recurring in living systems and contributing to make of Nature a truly unique model of sustainability. It is up to the developer to decide when to use these principles to inform the design process and up to which level of compliance the solution should aim at.

It is not the main objective of this paper to explain in detail the approach and methodology, but to report about its application on a specific problem so as to show the logic behind the process and its potentiality for innovation. The chart n.1 at pag.9 summarizes the overall process providing the flow of the iterative process undertaken with short description. The detailed explanation is provided in the following pages.

The Challenge addressed:
The Challenge targeted Food Systems in general and how to make them more sustainable. Being Food Systems highly complex to be tackled in their entireness, a specific context - or element of the overall food system - was selected which was more familiar to the team. A context affected by challenges whose solutions could, as leverage points, triggers significant positive changes to the global systems. The context selected was arid/semi-arid seawater coastal areas of Developing Countries affected by water scarcity, land degradation and with an increasing population. In particular the team determined that the lack of water (associated with its bad management) is one of the key factors responsible for degrading lands, preventing land (and ecosystem services) regeneration and therefore decreasing food production which is affecting especially coastal poor communities. Consequently the team formulated a more specific challenge:

How to produce fresh water at low cost in arid/semi-arid seawater coastal areas so as to facilitate reducing land degradation/regenerating land productivity and other ecosystem services and allow local communities, especially poor ones, to develop and grow.

2. 1st Scoping phase: Land degradation in arid coastal area

This phase aimed at carrying out a functional analysis of the challenge. Which were the functions the solution had to carry out in order to solve the challenge? The team explored two main aspects:

Land degradation-regeneration:
In the arid/semi-arid environments, land degradation is caused by wind erosion and salinization, loss of organic substance, sealing and compaction exacerbated by bad land management practices with consequent loss of productive soil and vegetation. In these regions, soil conservation and rehabilitation are essential for sustainable agriculture and improvement of dry land ecosystem. *Revegetation* is one of the most effective means to control soil degradation and to rehabilitate degraded lands. Therefore *a crucial element to regenerate soils is to restore or increase their water content* so as to assist revegetation practices by improving the structure of these soils and reduction of rain water run-off[ii]. Increase of water content would initially help improving the biological activity of the soil; for instance revitalizing cyanobacteria already present in the top-soil[iii] which are nitrogen-fixing and can intercept and store sporadic water or introducing bacteria existing naturally in the rhizosphere of plants in normal conditions (Mycorrhizal fungi, Rhizobium and symbiotic bacteria, Azotobacter). *Once the soil reaches a minimum level of water and nutrients, revegetation could start using model of succession of plants*[iv]. In general, the progressive increase of organic matter will influence the physical conditions of a soil in several ways: plant residues that cover the soil surface will protect the soil from sealing and crusting by raindrop impact; roots of plants will further increase rainwater infiltration; plants adapted to arid lands (*Xerophites*) could be used whose physiological and morphological features will help trapping air moisture; and soil macrofaunal activity (i.e.: earthworms) will further increase soil porosity and organic content.[v]

Water issues and Desalination:
In arid/semi-arid seawater coastal areas there is obviously an abundance of water but need to be desalinated and brought up from sea level to the land for different uses. Depending on specific locations there could be additional amount of fresh water available as surface and groundwater, rainfalls and air moisture. These resources are however limited and unpredictable so that they might not guarantee the daily minimum water demand for basic needs and productive activity of coastal communities unless complex and expensive systems for gathering and storing would be set up (for instance through technologies such as dams, rain harvesters, artificial aquifers, fog catchers etc..)[vi] with, sometimes, detrimental effects to the local ecosystems.
In high income arid seawater coastal communities - such in the Middle East Countries - desalination is still considered the best option to satisfy a constant, large and, if needed, growing water demand for drinking water, water sanitation and industrial/productive activities. This is also true especially when existing coastal fresh water resources have been compromised (due to over-exploitation and saline intrusion) and costs for recovery would be higher than investing in desalination. A number of suitable technologies are available to provide desalinated water, but costs are still too high to justify the use of this water for agriculture; even less for regenerating degraded soils.
The use of desalination technology by poor communities is still limited by the following factors:
- High capital expense for infrastructure. High-energy demand and dependence on fossil fuels.
- Lack of accessible spare parts, consumables and M&O skills.
- Lack of modularity and capacity for decentralization of existing technologies.

For instance, as a general reference, small mobile Reverse Osmosis (RO) desalination units producing around 5 m^3/day can cost around 10.000 $ (without considering opex costs) and the cost for produced water can reach more than 10$/$m^3$ (0,01$/l), investment and costs still too high to be afforded by poor communities unless heavily subsidized[vii].
The cheapest desalination technology available in terms of investment and water cost is the solar still. *Solar still* units have been already used for desalinating seawater on a small scale for families or small villages in developing countries and in remote islands where solar energy and low cost or donated labour is abundant, but electricity or access to cheap fossil fuel is not. Several suppliers are now offering ready-made units, and the typical cost of a system capable of supplying 10lt/day is around $750. If the solar still is built with local material and using local labour, the cost can drop to 200-300$ (excluding costs for pumping seawater and distribution). This technology, modular, could be multiplied so as to provide water to an expanding community[viii].
From the analysis above, at first glance, it looked as if "desalinate seawater" to produce fresh water for soil regeneration was the main function to be explored. The team entered into the Discovery Phase with the following questions: *Is desalination the only solution? And if yes, how could be made so cheap to be used for the soil?*

3. 1st Discovery phase: looking at coastal ecosystems

The Discovery phase aimed at identifying organisms and ecosystems and study them so as to identify different strategies and mechanisms to carry out similar function(s). These strategies are utilized to inform the design and innovate it. The very multi-disciplinary nature of this biomimicry approach requires the involvement of biologists who can work with engineer and designer to pin point at the appropriate living systems and assist in the creative process.
After the scoping phase there was an obvious interest in exploring desalination processes in Nature. So to find out ***"How does Nature desalinate salty water?"*** so as to discover possible innovative ways to make desalination processes more efficient and affordable also to the poor people. However studying different organisms dealing with salty water in different contexts, Nature kept on suggesting that to find a solution to our complex problem the team should have looked at it with a *systemic perspective*; the team should have not necessarily focused at desalination as a process to be improved, but, first of all, at how desalination was put in the broader context of water management in a whole ecosystem.
The new questions the team explored were: *"How does nature build ecosystems (communities) in arid/semi-arid seawater coastal areas?"* or even more generally *"How does Nature create conditions conducive to life to develop and grow in arid/semi-arid seawater coastal areas?".* To answer this question the team focused the investigation on seawater coastal ecosystems. In particular the *Mangrove Ecosystem* and *Salt Marshes* were selected which are ecosystems thriving in contexts similar to the one of our challenge: hyper-arid/arid/semi-arid seawater coastal areas. This was also an attempt *to solve local problems looking at natural local solutions.*

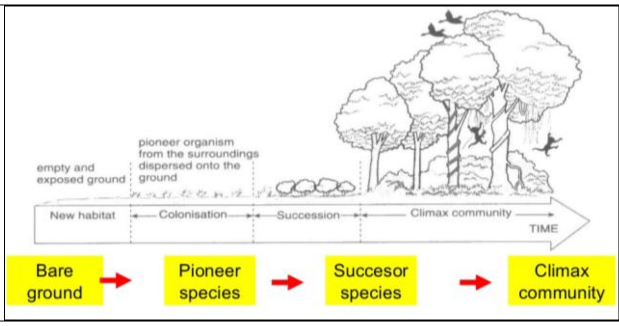
Briefly about Mangrove Ecosystem (or *Mangal*)
Mangroves are salt-tolerant forest ecosystems found mainly in the tropical and subtropical intertidal regions of the world. They grow along protected sedimentary shores especially in tidal lagoons, embayment and estuaries. They also can grow far inland, but never isolated from the sea. The Mangal is a broad domain encompassing the entire biotic community comprising of individual plant species, associated microbes (like bacteria and fungi) and animals. The Mangal is a highly productive ecosystem despite it is generally nutrient deficient especially in nitrogen and phosphorus, with productivity about 20 times more than the average oceanic production. Intense and diverse microbial activity in mangroves, including Nitrogen- fixing and phosphate-solubilizing microorganisms, is responsible for retaining the scarce nutrients within the system, and that restoration of these tropical ecosystems depends on the health of the microbial benthic communities and conservation of their geochemical environment.[ix],[x],[xi]

Avicennia

Briefly about Salt Marches
Salt marshes are important transitional habitat between the ocean and the land; they are estuaries where fresh and salt water mix. Salt marsh plants are salt tolerant (halophytes – e.g. *Salicornia*) and adapted to water levels that fluctuate with the tide. Tides carry in nutrients that stimulate plant growth in the marsh and carry out organic material that feeds fish and other coastal organisms. Over time, salt marshes accumulate organic material, forming into a dense layer called peat. Like Mangrove, Salt marshes are among the most productive ecosystems on earth. Salt marshes can be extremely difficult places to survive because of wide daily fluctuations in salinity, water, temperature, and oxygen. Few plants have evolved adaptations to cope with the extreme conditions of salt marshes[xii]. When sediment supply is sufficient, salt marsh vegetation can accumulate extensive amounts of fine-grained sediment, which can result in the formation of a salt marsh plateau.

Salicornia

Briefly about Ecosystem Succession:
Both Mangal and Salt Marshes can be described in terms of phases of development which include **Pioneer species** (e.g. *Avicennia* for Mangroves and *Salicornia* for Salt Marshes), which are the first to colonize empty ecological niches or previously disrupted ecosystems, beginning a chain of **Ecological Successions** which concerns the gradual process where one community changes its environment so that it is replaced by another, which will ultimately lead to a more biodiverse steady-state ecosystem, the **Climax**.



Below the main considerations which emerged from the investigation into Nature and which we considered to abstract design strategies to respond to our challenge:

- From an ecological perspective, mangroves and salt marshes are unique and significant ecosystems. They support a diverse range of organisms (plants, animals, bacteria and fungi). In fact these plants have been so successful in their development that are among the most productive natural systems found throughout the world.
- Both ecosystems have *pioneer species* (e.g. *Avicennia* for Mangrove and *Salicornia* for Salt Marshes) which are adapted to high saline environment. They are the first species to colonize a high salinity coastal environment and represent therefore the initial stage of the upcoming complex ecosystem. Thanks to their adaptation, *they start creating conditions conducive to other species to appear and survive.* They kick start a progressively self-sustaining process of collection of nutrients and water (through trapping of rare rainfalls, increase air moisture and its collection, reduce evaporation via shading, etc.) so as to allow other species to appear in a process of succession and zonation which will finally form a mature ecosystem.
- *In coastal terrestrial ecosystems desalination is only one element of an integrated water resources management, however it seems a crucial one, the starting strategy upon which other natural strategies to get fresh water would build upon.*

4. 1st Creating Phase: Starting regenerating soils using desalination

From the considerations above the team formulated that *a desalination process could be indeed the first element to be considered in seawater coastal areas in order to obtain fresh water where it is not available. However, in medium-long term, it has not to be the only strategy, but rather the starting one* which:

- Will help the formation of fertile soils and initial growth of plants with consequent changes in soil texture and microclimate and increased capacity of the building ecosystem to access, generate and store fresh water.
- Will allow local communities to start generating food and income from agriculture.

Therefore the team distilled from Nature the following broad design strategy which could solve the initial challenge (as formulated in section 1 of this paper):

A financially viable desalination process that allows desalinating and distributing enough fresh water to kick start a process of land productivity (re)generation which progressively generate conditions conducive to other alternative water resources to become accessible.

Is there an already existing desalination technology which could be improved as it already (at least partially) complies with the above strategy? According to the investigation of the 1st scoping phase the team considered the *Solar Still* as the most suitable technology. Therefore the Biomimicry Thinking process was re-iterated in order to improve the design of the solar still and the following new *sub-challenge* was defined:

How to improve the Solar still so as to make it suitable to tackle our main challenge?

5. 2nd Scoping Phase: functional analysis of the Solar Still and its applicability

Different designs for Solar Still have been developed and tested in the last thirty years in order to increase their efficiency. Many of them remain at experimental level because of the complexity of their design or costs not affordable by poor communities. Few have been commercialized but sold at high prices (100-600$/m^2$) and mainly utilized in gardening by environmentally conscious people. To maximize its yield (lt/day/m^2 of distilled water), a solar still has ***to***

optimize the evaporation/condensation process. This optimization can be achieved through the combination of several sub-functions such as:

- *Optimize surface/volume ratio*
- *Optimize Light interceptance*
- *Optimize gradients of temperature*
- *Move/distribute fluids*

Research aiming at increasing the efficiency of Solar Still technology focused on the following conditions[xiii]:

1. *Maintain a high feed water temperature*. This can be achieved if:
   - A high proportion of incoming radiation is absorbed by the feed water as heat. Hence low absorption glazing and a good radiation absorbing surface are required
   - Heat losses from the structure are minimum
   - The feed water in the still is shallow
   - An anti-reflecting/heat trapping material is inserted in the water basin such as black wick or gravel/carbon.
2. *Increase the temperature gradient between feed water and condensing surface* (this makes the process evaporation/condensation more efficient). This can be achieved if:
   - The condensing surface absorbs little or none of the incoming radiation
   - Condensing water dissipates heat which must be removed rapidly from the condensing surface.
3. *Increase evaporation surface*. This can be achieved if:
   - Wick material or sponges are inserted in the basin so as to increase the evaporation surface.
4. *Reduce vapour leakage*. Seal all possible leakages in the structure.

In order to make the solar still more efficient but also improve its applicability for land (re)generation, it needs to satisfy other technical/financial requirements which are usually not considered in current research such as:

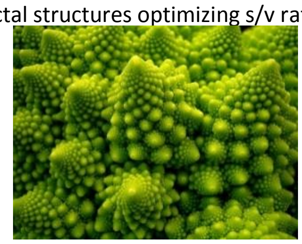
- *Modularity and Movability;*
- *Being light but sturdy;*
- *Easy to be assembled, dismantled and operated;*
- *Allow salt recovery;*
- *Affordable by poor communities.*

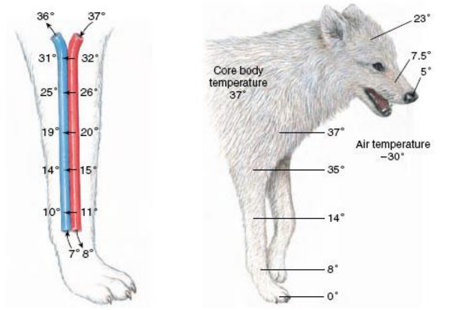
6. 2nd Discovery phase: looking at several Nature's strategies

Again, following the functional analysis above, the problem was "biologized" through the following question: *How does Nature optimize the condensation/evaporation process?* And decomposing it in sub-functions: *How does Nature:*

1. *Optimize surface/volume ratio*
2. *Optimize Light interceptance*
3. *Optimize gradients of temperature*
4. *Move/distribute fluids*

Because of the several sub-functions identified and requirements needed, instead of exploring natural champions to be emulated for each sub-function, the team investigated recurring natural strategies and mechanisms utilized by several living systems to carry out similar functions.

Biological analogy	
1. *Optimize surface/volume ratio* This is a general strategy in nature. The ratio Surface/Volume is designed in order to optimize exchanges of energy and matter from/to the inside of an organisms to/from the outside environment. In order to do this <u>*elaborated surfaces following fractal geometries/hierarchically structure are often found in plants and animals*</u>. Some examples among many: vascular and respiratory systems in animals and plants allowing transport and exchange of fluids and thermoregulation or folding/deployable structures such as ferns, insects wings, etc.	fractal structures optimizing s/v ration 
2. Optimize light interceptance In plants regulation of interceptance of light is carried out through strategies which are compromises between the need to photosynthesize and the need to regulate evapotranspiration. In a competing environment such as a forest, a recurrent strategy is to deploy different leaf size and shape, which can occur also within an individual plant: smaller leaves produced near the top where irradiance is highest and evapotranspiration too, and larger leaves towards the interior where light is lower as well as the loss of water by evapotranspiration. Another way to regulate light interception is by changing leaf angle and/or orientation. <u>*Vertical arrangements enhance interception of light at low sun angles during early morning*</u>	Vertical and horizontal leaves  

<table>
<tr><td><u>or late afternoon, and reduce interception at solar noon when radiation levels are highest. Leaves that are displayed horizontally will intercept light all day long, but especially around midday.</u></td><td></td></tr>
<tr><td>3. Optimize gradients of temperature
In order to maintain the optimal temperature for metabolic functions, complex organisms like mammals <u>retain or dissipate heat through a counter-current heat exchange</u> between the outgoing warm blood and the returning cold blood. For instance arterial blood in the leg of an arctic mammal or bird passes in close contact with a network of small veins. Because arterial blood flow is opposite to that of returning venous blood, heat is exchanged very efficiently from artery to veins. By the time the arterial blood reaches the foot it has transferred nearly all of its heat to the veins returning blood to the body core.</td><td>


</td></tr>
<tr><td colspan="2">4. Move/distribute water (and salty water)
In order to move fluids such as water, organisms exploit water potential. Deploying strategies that are using processes such as <u>capillarity</u>, osmosis, and evapotranspiration. Vascular plants are able to transport water from roots to the leaves via a complex process involving capillarity and evapotranspiration. This process is not yet fully understood and quantifiable. Plants that survive in saline environment (such as mangrove) are able to use salty water for their functioning deploying strategies to neutralize the salt and expel it (using salt glands). However from time to time they need to purge their water channels from salt otherwise their metabolism would be compromised. Do to that they count on occasional rains and fresh water floods.</td></tr>
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7. 2nd Creating Phase: the Mangrove Still

Following the above the team *reviewed the current <u>passive</u> solar still technologies vis-a-vis these strategies to see if and how these are already embedded in the current design and eventually improve it*. Following this analysis the team proposed the design of two improved solar stills (fig.1 and 2) which were named ***Mangrove Stills*** (in reference to the main biological analogy with the Mangrove ecosystems). In the table below a description of the solutions inspired by Nature.

Functions	Optimized Design
1. Optimize surface/ volume ratio ***2. Optimize light interceptance***	In order to increase the evaporative surface exposed to sunlight it is proposed to create an overall transparent structure of the still with increased evaporating and condensing surface vis-a-vis the volume of the still. This is done using an **undulated sheet made in transparent-sunlight resistant polycarbonate** bent so as to create a **tubular (or semi-tubular) structure**. Inside the structure an undulated trough, made of the same undulated material would be inserted. Undulated surfaces are wider (around 15% more) than flat ones with the same projection (depending on the period of the sinusoidal shape), this means more surface exposed to the sun compared to volume and available for evaporation and condensation. Furthermore the undulation increase resistance to bending moment compared to flat one. The design allows the use of a single undulated transparent sheet commercially available in DIY shops to easily build up almost the whole structure. The tubular/semi-tubular structure is almost fully transparent (apart the closures at the two sides of the structure) so sunlight can reach the evaporation surface for longer period of time than usual solar stills and orientation of the still toward the sun can be more flexible. Because of the volume created by the tubular structure above the trough and its full transparency, black wick materials and sponges could be inserted in the trough so as to increase evaporation surface but avoiding shading each other. Orientation of the wick material has been chosen emulating the leaves orientation (horizontal and vertical leaves) so as to reduce shadings. An additional strategy to increase light on the still is to add a solar concentrator made by a simple aluminium foil positioned on the „back side" of the still compared to the sun direction.
3. Optimize gradients of temperature	In order to increase the gradient of temperature between the evaporative surface and the condensing one (so as to increase the yield of the still), the following **counter-current heat exchange process** is set up: Seawater will be sprayed over the tubular structure from perforated pipes (or it will be let drain on the upper part of the still). The seawater will drip down the side of the still and having lower temperature than the surface of the still it will cool it down and will get pre-heated. The water will be collected in a semi-circular undulated compartment around the lower part of the still and will enter the still. So the overall process will allow to cool down the condensing surface and heat up the evaporative one. In case of rainfall this practice will also allow to clean the external surface of the still from accumulated salt and purge the whole system with fresh water so as to avoid formation of crystals of salt in the wick material (the same purging process needed by the Mangrove). Furthermore in case of rainfall it could be foreseen to disconnect the seawater feed-in and use the still as rainwater harvester. To increase further the yield of the still, compartments for inserting *heat storing material* below the trough and in the sides of the still have been foreseen so as to trap some daily heat and release it during the night for prolonging the operation of the still also without sunlight.
4. Move/ distribute water and salty water	The shape and transparency of the still allow introducing wick materials and sponges in the trough in horizontal and vertical strips (we put cuts from black cotton T-shits to test) so as to move and distribute water by capillarity also in vertical planes and therefore increase evaporation surface.

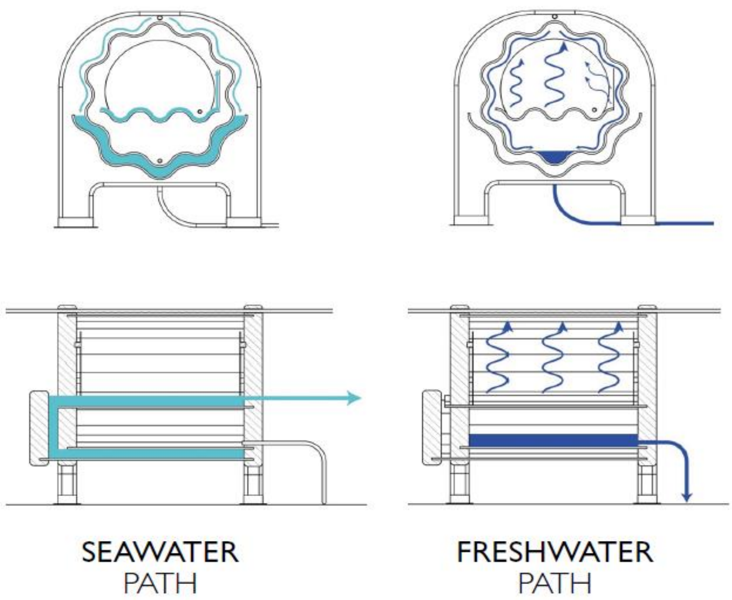


Fig.1 Operation of tubular Mangrove Still

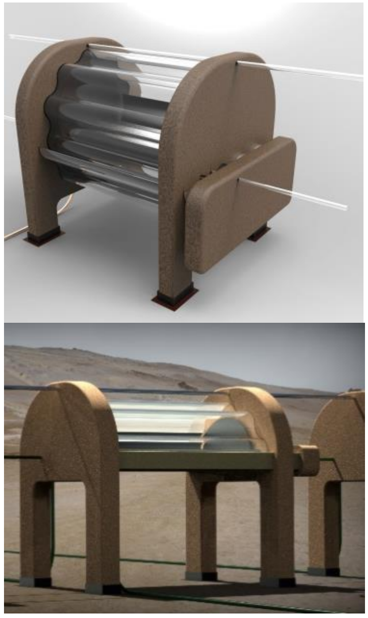


Fig.2 Tubular and Semitubular Mangrove still

8. Proof of Concept: initial prototyping

An early prototype of the semi-tubular and tubular Mangrove Still have been built to test the process and the performance. Eight thermocouples k-type and a data-logger were used to measure temperature gradients during the day and for different position of the stills in the same location (Trento-Italy). The stills tested were 68x45cm with an internal trough of around 60x40cm. Salty water was collected from the Mediterranean Sea (Tuscany). Below we report about a test.

Below some picture of the tests:

 Fig.3: Semi tubular Mangrove Still	 Fig 4: Tubular Mangrove Still
 Fig. 5: Trough inside the still and MS with example of reflective surface	• 1300kWh/m^2 average irradiation (Trento-Italy) • Estimated Water production: 1.10 l/day/m^2 (10am-19pm) • Measured: 0.25 l x 0.24 m^2 without counter-current heat exchange and reflective device • Investment cost: 20$ for 1m^2 of still at EU prices

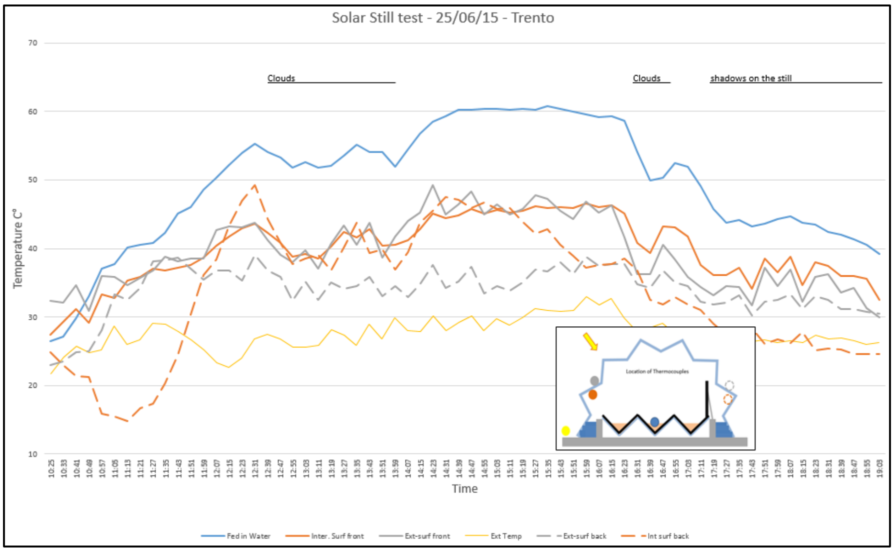


Fig.6: Example of tests with thermocouples of the semi tubular MS

It should be highlighted that the final amount of water estimated (around 1 l/day/m^2) is affected by the following factors[xiv]:

- Not appropriate cooling of the structure via dripping feed water was tested. According to literature this manoeuvre could improve efficiency by up to 20% [xv](if properly set, otherwise it could be also slightly detrimental);
- No reflective surface was added. This manoeuvre could increase efficiency of around 20% throughout the year;
- No heat storing material was put in the semi-tubular still. This manoeuvre could increase daily production of around 30%;
- Distributed leaks at the bottom and sides of the stills because of bad sealing and because the polycarbonate structure cracked the polystyrene in several points. Losses can be estimated around 20-30%;
- Not yet optimized shape of the top of the stills which caused at least 15-20% of condensed water to drop back into the trough instead of sliding down the side;
- Some distilled water remained inside the stills because trapped in the trough structure and because of lack of appropriate slopes to drain out;
- Various leaks of vapour because of the positioning of the thermocouples;
- Location of the tests not compatible (low irradiation) with foreseen location of operation of the stills.

All the above issues have been noted and can be easily solved in the next prototypes.

Therefore we believe that further optimizations in the design could bring to a production of at least ***3-3,5 l/day/m^2*** in appropriate locations and weather conditions. Considering the cost for building the still (around 20$ per m^2 of evaporation surface), the Mangrove still has the potentiality for becoming competitive with other solar still existing in the market and object of researches (see fig.7 below).

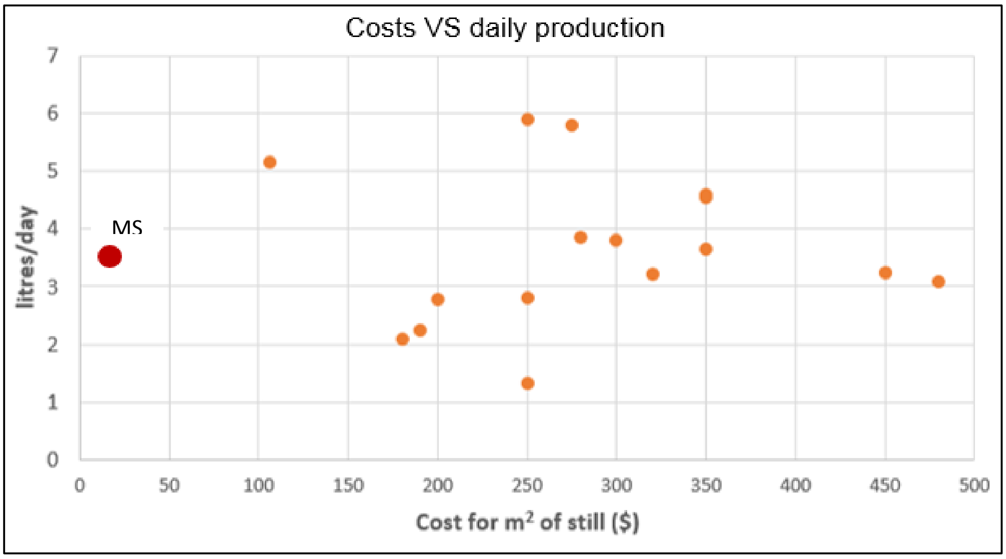


Fig.7: Cost analysis of different solar still configurations from [viii] – Mangrove Still located in the chart as (MS)

9. Planning and Operability for Land Regeneration

Because of its modularity and lightness, the solar stills could be assembled in systems of networks according to different configurations in order to produce and distribute fresh water to the land. Distilled water will be send to the soil via drip irrigation pipes. The presence of greenhouses might optimize the process reducing water evaporation from the soil.
Suitable practices for soil regeneration and revegetation should be applied to the specific context (e.g. in the Mediterranean region coastal species such as *Psammophytes* and *Ammophila* grass could be selected). Suitable plants should be selected so as to follow principles of Permaculture.
As provisional idea to be tested, a continuous flow of seawater could pass through the stills increasing its level of salinity (and temperature) till a final evaporation pond at the end of the circuit (the pond shall be close to the shore to avoid presence of high salinity water too much inland and allow discharging excess of salty water back to the sea). The pond whose water is left to evaporate, will allow production of salt. Alternatively the pond could be used for breeding brine shrimps (which can tolerate high salinity, even 7 times the one of seawater).
An alternative solution to concentrate the solar stills in a smaller space and collect distilled water in a central tank would be to assemble the stills on the sunny side of a special construction. This solution would most probably facilitate the management and control of the system.
Without tests in the field yet, it is premature to estimate how many square metres of land could be regenerated by the water produced by a single Mangrove still. However according to FAO's estimate of water needs for agriculture in arid areas, a single Mangrove still could regenerate around 8-10 m^2 of land.

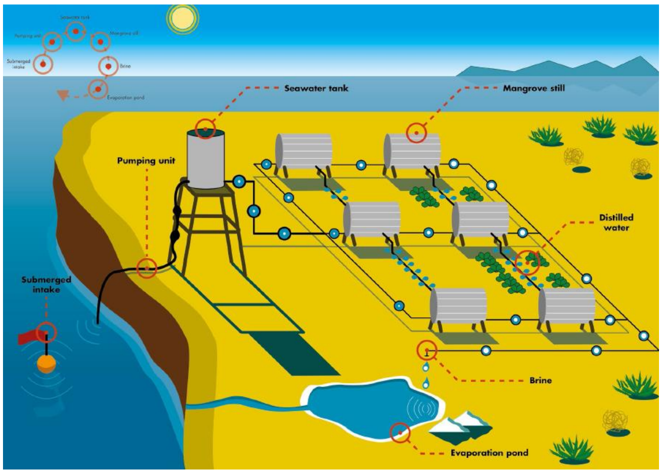


Fig.8: Distribute system of Mangrove stills

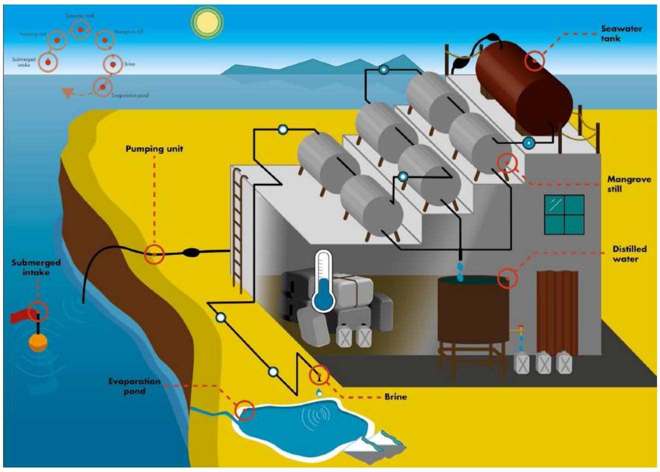
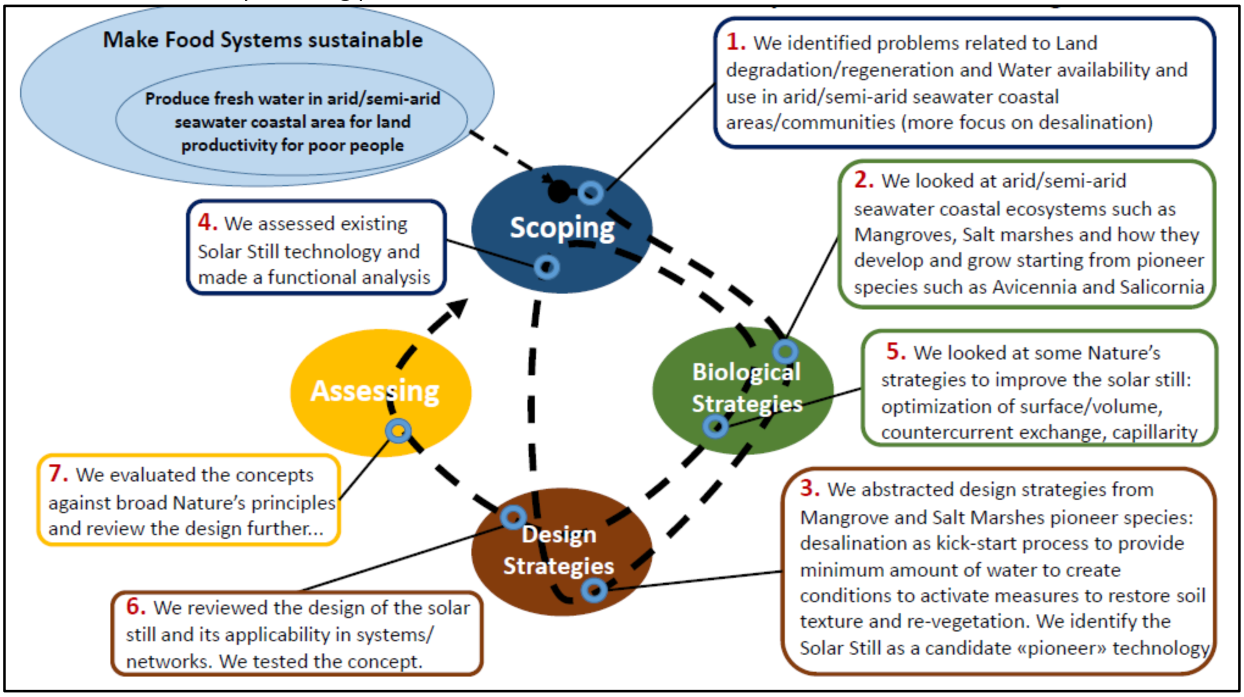


Fig.9: Centralized system of Mangrove Stills

10. Next Steps

The iterative Biomimicry Thinking process followed so far can be summarized in chart n.1 below.



The team is currently undertaking the following steps:

1: review of the design of the still: The initial design is under revision and each new solution is always determined taking inspiration from natural strategies and mechanisms. A revised prototype has been produced and it is currently under testing in Cyprus. Particular attention is been given to the selection of materials as they have to guarantee a certain performance in time, be environmental-friendly, locally available and cheap so as to keep the cost of the still around 20$/m^2.

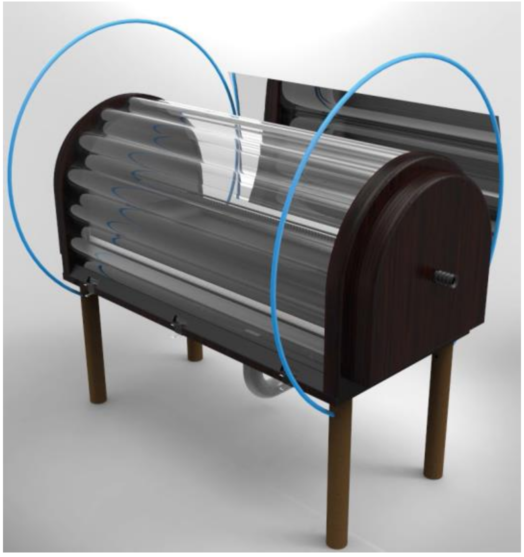


Fig.10: Revised Design of the Mangrove Stills

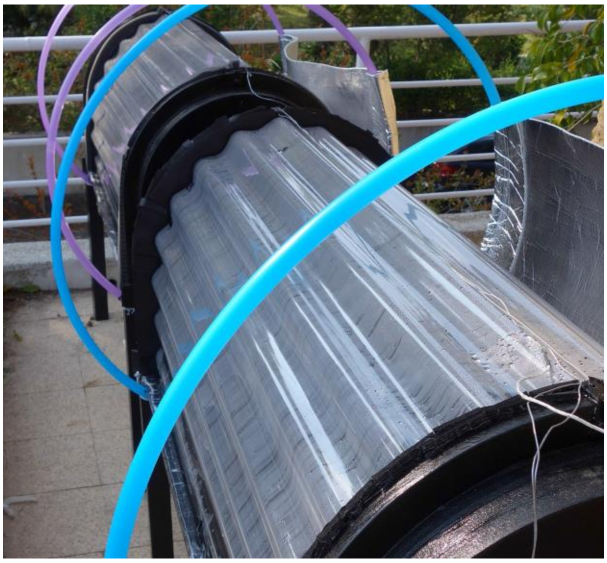


Fig.11: Prototype under testing

2: Testing in the field: a test combining the Mangrove still with actions aiming at regenerating degraded land is under preparation in Cyprus. The particular degraded conditions of soils in this island together with the availability of sunlight, is considered an optimal choice. In addition, tests are planned also to verify the applicability of the Mangrove still for treating polluted water (for instance to remove arsenic). This would greatly expand the market opportunity of the still.

3: preparing the numerical model: in order to make simulations on best materials, variant of design and orientation of the still, a numerical model is under preparation based upon energy and mass balance equations

4: Identifying the industrialization process/business model: currently there is no real market for solar stills. They are sold on-line for single users at prices between 100-500xm^2 (producing between 1-6 l/day/m^2) mainly for gardening purposes or utilized in limited amount for emergency actions to provide drinking water to population in Developing Countries (i.e.: Watercone, ClearDome, Rainmaker, Aquamate, etc.). All these stills have not been conceived to be linked into networks and to be used for providing water to regenerate land. Their high cost would prevent them to be cost effective in campaigns of land regeneration. The Mangrove still have been conceived exactly to be used for the land (this does not prevent it to be used for producing drinking water or water for other uses). An industrialization process and the business model are under definition which foresee the setting up of a network of partners such as:

- Suppliers of polycarbonate transparent sheets and undulated aluminium sheets.
- Producers/supplier of the main body of the still (the two sides closing the still via thermoformed empty elements)
- Companies specialized in solar/manual pumping systems to provide turn-key solution to clients
- Companies specialized in soil ecology and soil remediation to provide turn-key solution to clients
- NGOs engaged in projects in coastal areas of Developing Countries to identify testing/market opportunities.

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