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Fog farming: linking sustainable land management with ecological renaturation in arid areas by means of reforestation

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Abstract
There is plenty of water in one of the driest regions on earth. At vast stretches of South America's Pacific coast below the equator, dense fog is a common phenomenon and has been used for water production since the 1980s. This paper presents the results of a pilot project on periurban agri- and silviculture in Peru using fog as a water source.

Introduction
Water scarcity is the bottleneck for agriculture and development of Peru's coast and subject to aggravation due to climate change. Until present day, Peru's coast in general and the Lima Metropolitan Area (LMA) in particular have enjoyed to a great extend the effect of the country's high altitude glaciers that serve as a buffer for the capital's water demand during the highland dry season. However, climate models predict the disappearance of this buffer system below 5.500 masl by 2015, leaving one of the driest places on earth with yet another decrease in freshwater supply (Zapata 2008). The deviation of water resources from the highlands has led already to allocation conflicts. Peru is in urgent need of new concepts for water management.
Fog harvesting was introduced to South America in the 1980s and has since been implemented at various locations in North and Central America, Europe, Africa, Asia and Australia. The Standard Fog Collector (SFC) as described by Schemenauer and Cereceda (1994) has proven to be a successful instrument for this purpose. Apart from a number of small scale investigations, the design of the collector hasn't been substantially changed over the past three decades (e.g. Gioda et al. 1993). Within the framework of the presented project, financed primarily by the Global Exploration Fund, new fog collectors were designed at pilot and full scale.
Peru's coastline features hills (Span. "lomas") that up to a distance of 10-15 km inland are influenced by heavy fog from June through November. This ecosystem used to be hydrologically self-maintaining at a time when the hills were still forested. The trees collected the fog water and irrigated themselves; weeds and bushes also profited from this effect; the surplus water fed wells. Once the trees were cut the natural water cycle was interrupted and today during the dry season the Lomas resemble a desert. Although according to the findings of Ellenberg (1958) the feasibility of hydrological followed by ecological renaturation is reasonably high, tree saplings need a water source to reach a height that allows for the production of sufficient fog drip to be able to irrigate themselves. Once the reforestation has grown, the recovery of the water cycle would thus be possible (Tiedemann 2001).

Setting and Methodology
Setting: The project is set at the Bellavista settlement of the Lima suburb Villa María del Triunfo. Bellavista is a typical example for thousands of young dwellings with mainly plywood housing that were built during the last 15 years in terraces along the steep slopes of the Loma valleys.

Structural Improvement of Fog Collectors: The structure of fog collectors may be improved by considering two basic aspects: 1) the filling of space, i.e. the use of three-dimensional collectors and 2) the preference of vertical collection structures. These concepts led to the design of five pilot scale fog collectors of which we upscaled three collectors to the size of 8x4m and 4x2m, respectively. Figures 1 to 3 show the full scale collectors. Upon installation, water production of the new designs and the SFC (8x4m with double layer of 50% Raschel net) was measured daily until the end of the fog season 2007/2008.

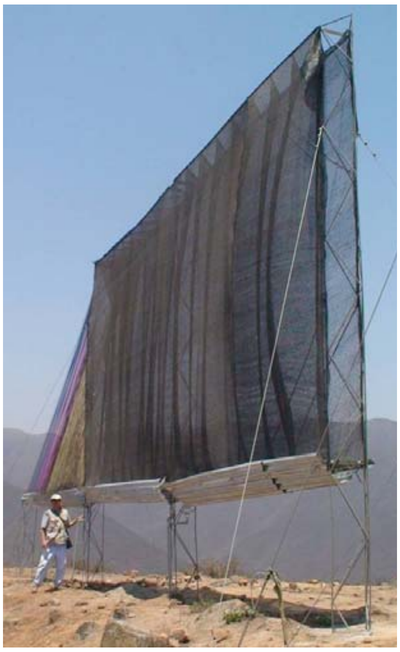

Fig. 1: "Eiffel" collector. 4x8x0.3m metal frame, two separated layers of Raschel 50% net with 10 additional strips in between

Fig. 2: "Harp" collector. 2x4x0.3m metal frame, 2,256m of 1.5mm rubber string vertically installed

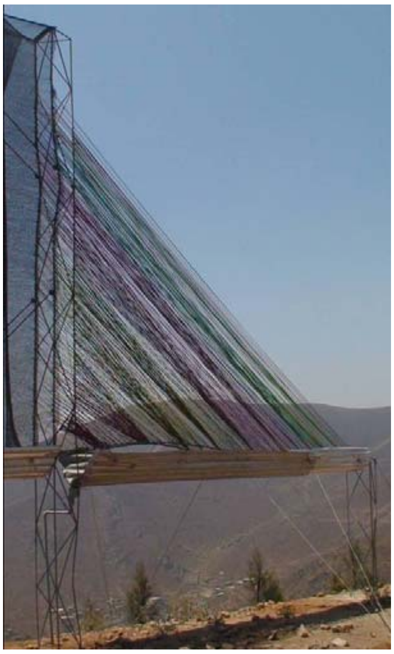

Fig. 3: "Diagonal Harp" collector. 2x4x0.3m metal frame, 1,520m of 1.5mm rubber string diagonally installed

Fig. 4: Tile collector. 5 *Casuarina* trees with collector and connecting channel made of tile.

Fig. 5: Tile collector with tubes. 5 *Casuarina* trees with tile collectors connected with tubes.

Fig. 6: Stone collector. 5 *Casuarina* trees with collectors and connecting channel made of stone and mud.

Fig. 7 (left): Funnel collector. 10 *Casuarina* trees with plastic funnels and PVC outlet.

Experimental tree collector systems: Fog harvesting from trees dates back to the aboriginal people of Tenerife and yields the advantage of potentially little maintenance efforts. In search of a robust collection system we experimented with 1) a collector consisting of tiles that form a collection surface and channel, 2) a collector consisting of tiles that form a collection surface which is connected by tubes 3) a collector made of stones and mud that form a collection surface and channel and 4) plastic funnels that were placed in a straight line under trees along the crestline (Fig. 4-7). Fog drip from these systems was collected in separate buckets and measured daily.

Reforestation: Along with the installation of the first three SFC and 100m³ in water storage capacity, a total of six plots were reforested at the Bellavista crestline with the purpose of identifying the most adequate tree species for hydrological renaturation. According to morphological and physiological characteristics we chose 1) *Casuarina cunninghamiana* (N=714), 2) *Schinus molle* (N=29), 3) *Acacia macracantha* (N=30) and 4) *Parkinsonia aculeata* (N=30) for these plantings that we refer to as *ecological reforestation*. *C. cunninghamiana* and *S. molle* are not native to the Lomas and were intended to be tested as nursing trees for the provision of natural fog drip as a source for ongoing reforestation with native species. After planting, growth and mortality were monitored over 10 months.

Urban Agri- and Silviculture: As a key aspect towards the target group's participation we implemented 10 small terraced family gardens for urban agriculture and a second reforestation area directly above the Bellavista settlement we refer to as *community reforestation*. *Caesalpinia spinosa* (Span. "Tara") was chosen for the community reforestation due to its conformity with the Loma ecosystem and the economic value of its non-timber products. 700 Tara trees were planted within this area between July and October 2007. The growth of the trees was documented one year after planting.

Results and Discussion

Structural improvement of fog collectors: The measurements of water production presented in Table 1 resulted in a high degree of distinction between the SFC on the one hand and the new designs on the other hand. All values are subject to a high standard deviation due to recurring periods of fog free days. Still, the measurements indicate up to sixfold higher maxima of water production of the Eiffel compared to the SFC, although both collectors cover the same collection frame of 8m x 4m = 32m² and nearly the same amount of space. The difference in mean values between Eiffel and SFC is even more pronounced than in the maxima; over the measurement period the Eiffel produced ten times the amount of the SFC at the same location. The interpretation of these patterns is the effect of the diagonal strips installed between the two main layers. These strips allow for fog collection even at fog events with wind directions that hit the collector sideways. With regard to the Harp collectors the data shows lower maxima but the mean values were similar or higher in comparison to the SFC – even though both of them expose a considerably smaller collection frame (4m x 2m = 8m² in case of the Harp collector and the same dimensions diagonally cut in half 4m x 2m x 0.5 = 4m² in case of the Diagonal Harp). Although the Harp designs showed the best surface-water yield ratio, in the interest of simplicity, reproducibility and robustness, we favour the Eiffel collector. Considering the limited space with optimum conditions for fog harvesting even at locations with high fog abundance, the achievements in fog harvesting efficiency might open another door into a broader field of application.

Table 1: Results of water production measurements of tested fog collectors; mean, maximum and minimum value with standard deviation (measurement period in brackets).

SFC (19.09.07-13.01.08)	mean	28.7 L/d
	max	598.7 L/d
	min	0.0 L/d
	std dev.	82.4 L/d
Eiffel (19.09.07-13.01.08)	mean	281.2 L/d
	max	2,651.6 L/d
	min	0.0 L/d
	std dev.	487.1 L/d
Harp (21.10.07-13.01.08)	mean	62.7 L/d
	max	200.0 L/d
	min	0.0 L/d
	std dev.	52.2 L/d
Diagonal Harp (20.10.07-13.01.08)	mean	28.6 L/d
	max	94.2 L/d
	min	0.0 L/d
	std dev.	24.1 L/d

Tree collectors: Taking into account the ratio of drip collecting surface and amount of collected water, the ceramic channel with tubes showed the best results. The stone channel let too much water seep into the ground which thus never arrived in the collection buckets. The funnel system had the disadvantage that the tubes at the bottom of the funnel were blocked by material falling off from the trees. Since dust and falling leaves also affect the channels on the long run, it is recommendable to use a channel with a higher brim and a screen at the tube inlets (Lummerich 2008).

Table 2: Results of water production measurements of tree collectors; mean, max. and min. value with standard deviation (measurement period in brackets).

Tile collector (12.07.07-13.01.08)	mean	1.4 L/d
	max	17.6 L/d
	min	0.0 L/d
	std dev.	2.0 L/d
Tile collector with tubes (12.07.07-13.01.08)	mean	1.6 L/d
	max	18.0 L/d
	min	0.0 L/d
	std dev.	2.3 L/d
Stone collector (12.07.07-13.01.08)	mean	0.1 L/d
	max	6.1 L/d
	min	0.0 L/d
	std dev.	0.6 L/d
Funnel collector (20.10.07-13.01.08)	mean	1.6 L/d
	max	8.2 L/d
	min	0.0 L/d
	std dev.	1.6 L/d

Reforestation: During the first year of the project the water provided by the SFCs was used for the irrigation of a pioneer grove on the hilltop as future natural fog collectors and as the initiation of the recovery of natural Loma water cycles. After one year, the hilltop trees had reached a mean height of 148.7cm and thus had grown independent of irrigation by covering their water demand by their own fog collection. Although Table 2 indicates preference towards *S. molle* and *P. aculeata*, observations one year after termination of irrigation favour the latter and *A. macracantha*; *S. molle* suffered 90% mortality. An increase of natural vegetation at the project site entails the assumption that locally the natural water cycles can be restored.

Table 2: Growth patterns of tree species in ecological reforestation over measurement period.

	October 2006		July 2007		Increment of growth [%]	Mortality [%]
	N	Mean height	N	Mean height		
Casuarina cunninghamiana	714	96.5	641	149.4	55%	10%
Schinus molle	29	51.2	28	67.3	31%	3%
Acacia macracantha	30	57.4	23	93.0	62%	23%
Parkinsonia aculeata	30	90.1	29	109.1	21%	3%

Urban Agri- and Silviculture: During the second year the water was used for family horticulture and a plantation of 700 *Caesalpinia spinosa*. By April 2009, the Tara plantation had reached a mean height of 98.7cm and is expected to give a first harvest by 2010. A key to the successful implementation was the high commitment of the community that was involved in every step of the project and that worked over months in “faenas” (community work on Sundays) in the construction of reservoirs and the maintenance of the installations and plantations. As people valued fog collection and reforestation uphill as a water supply for cash crops other villages took the initiative to copy the project. The motivating effect of these measures was threefold: 1) among the requirements for the young settlements to achieve legal land titles, the Peruvian legislation demands a reforestation area above the settlement as a protection against landslides; 2) the selling of Tara fruit and of the harvest from the family gardens adds an economic value to fog harvesting, 3) a source of income close to the village is especially important for single mothers. So far the project concept has been copied by two neighbouring villages.

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