Fog collection as a strategy to sequester carbon in drylands

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HIGHLIGHTS

- Advection fog is the sole source of water for many near-the-sea areas worldwide.
- We present the results of a long-term reforestation project in the Atacama Desert.
- Trees were irrigated with artificially fog-collected water for three years.
- After 15 years from planting, about 65% of trees were still alive and growing.
- Reforestation induced fast and substantial carbon sequestration.

GRAPHICAL ABSTRACT
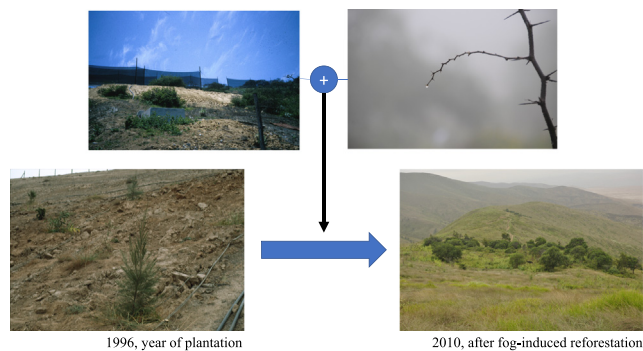
1996, year of plantation   2010, after fog-induced reforestation

ABSTRACT

Advection fog is the sole source of water for many near-the-sea arid areas worldwide such as the *lomas*, i.e. fog-dependant landscapes of the coastal zone of Peru and Northern Chile, where deforestation occurred since 16th century, leading to a progressive and severe desertification. There, today's local socio-ecological systems suffer from lack of freshwater because they cannot rely anymore on the contribution of fog captured by vegetation. This paper presents the results of an experimental reforestation project carried out in Mejia (Peru), where tree seedlings of five native and exotic species were planted in two permanent plots in 1996. Part of the seedlings were irrigated during the first three years after planting, others not. The irrigation was carried out thanks to water harvesting by large fog collectors. From the third year onwards, all trees relied only on fog water collected by their canopy. Survival rate, height, and root-collar diameter were monitored until 2010, when also the soil carbon and nitrogen stocks were measured. Fifteen years after the planting, about 65% of trees were still alive and growing, and reforestation had induced substantial carbon sequestration both above- and below-ground. Of the tree species, *Acacia saligna* was definitely best performing than the other, with most of the above ground carbon stored in its biomass and a consequent high efficiency as natural fog collector. Overall, the combination of fog collection by nets and the plantation of trees showing good fog collection capacity, represented a successful strategy for allowing reforestation of arid environments and induced fast and substantial carbon sequestration. Greater efforts should be thus devoted for this purpose, paying special attention to the selection of the most suitable tree species to plant, especially looking at the local biodiversity.

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This work is dedicated to the memory of Professor Mario Falciai, passed away in 2015, who firstly conceived the experiment and attended all the work since 1996, bringing in our University the idea of Fog Collection for sustainable water management.

1. Introduction

Since the dawn of Anthropocene, the current epoch of Earth's history when humankind has joined with the other environmental forces in shaping the planet, the human impact on global natural resources has been major (Crutzen, 2002; Certini and Scalenghe, 2015). To accommodate the need for food, energy, shelter and water of the relentless growth of human population, forest cover has been progressively reduced. One of the major results of the process was the creation of anthropogenic deserts (Le Houérou, 2002) in many parts of the world. Peru is one of the most dramatic examples of land cover transformation, deforestation and overexploitation of forest resources. Although the earliest evidence of human presence in Peruvian territory have been dated to approximately 9000 BCE, the oldest known complex society there flourished along the coast of the Pacific Ocean between 3000 and 1800 BCE (Haas et al., 2004). Sandweiss (2003) reports that, according to archaeological sites interpretation, south of 12°S in coastal areas of Peru, Sea Surface Temperature was cooler than the range from the Terminal Pleistocene through to the present. Modern climatic conditions and range of interannual variability were established along the entire Peruvian coast at about 3000 BCE.

In mid-16th century, following the Spanish conquest, an unprecedented exploitation of natural resources began (Belknap and Sandweiss, 2014). Hence, the *lomas* (Spanish for "hills"), i.e. the areas of fog-watered vegetation in the coastal strip of Peru and Northern Chile at elevation ranging from approximately 600 m to 1200 m a.s.l., were plundered for timber and fuelwood and not replanted, with the consequence that, nowadays, these areas are barren and among the driest regions on Earth. In addition, *lomas* have been impacted by unregulated grazing and, occasionally, mining.

Local communities rely on little water for drinking, washing, or sanitation, and do not have water for irrigation. From May to November, the Humboldt ocean current cools the water-laden air coming from the Pacific. The current is also largely responsible for the aridity of Atacama Desert in northern Chile and coastal areas of Peru. Marine air is cooled by the current and thus is not conductive for generating precipitation, although stratocumulus clouds (often perceived as fog) are produced. Here, the stratocumulus clouds meet the coastal ridge, producing highly dynamic advective marine fog, a major feature of the local climate that provides water to the arid environment. There are several adaptation mechanisms by organisms to use as efficiently as possible the water of advection fog. Trees build a complex architecture of branches that constitutes, both in young as in mature trees, an excellent tangled mist interceptor of fog. Collecting recurrent fogs by wide screens built up of a net of fibres (currently the polypropylene Raschel mesh in use in tree nurseries) has been shown to be a viable source of good quality water in many arid parts of the world (Schemenauer and Cereceda, 1991; Klemm et al., 2012), including Peru (Vince, 2010). The up-taken
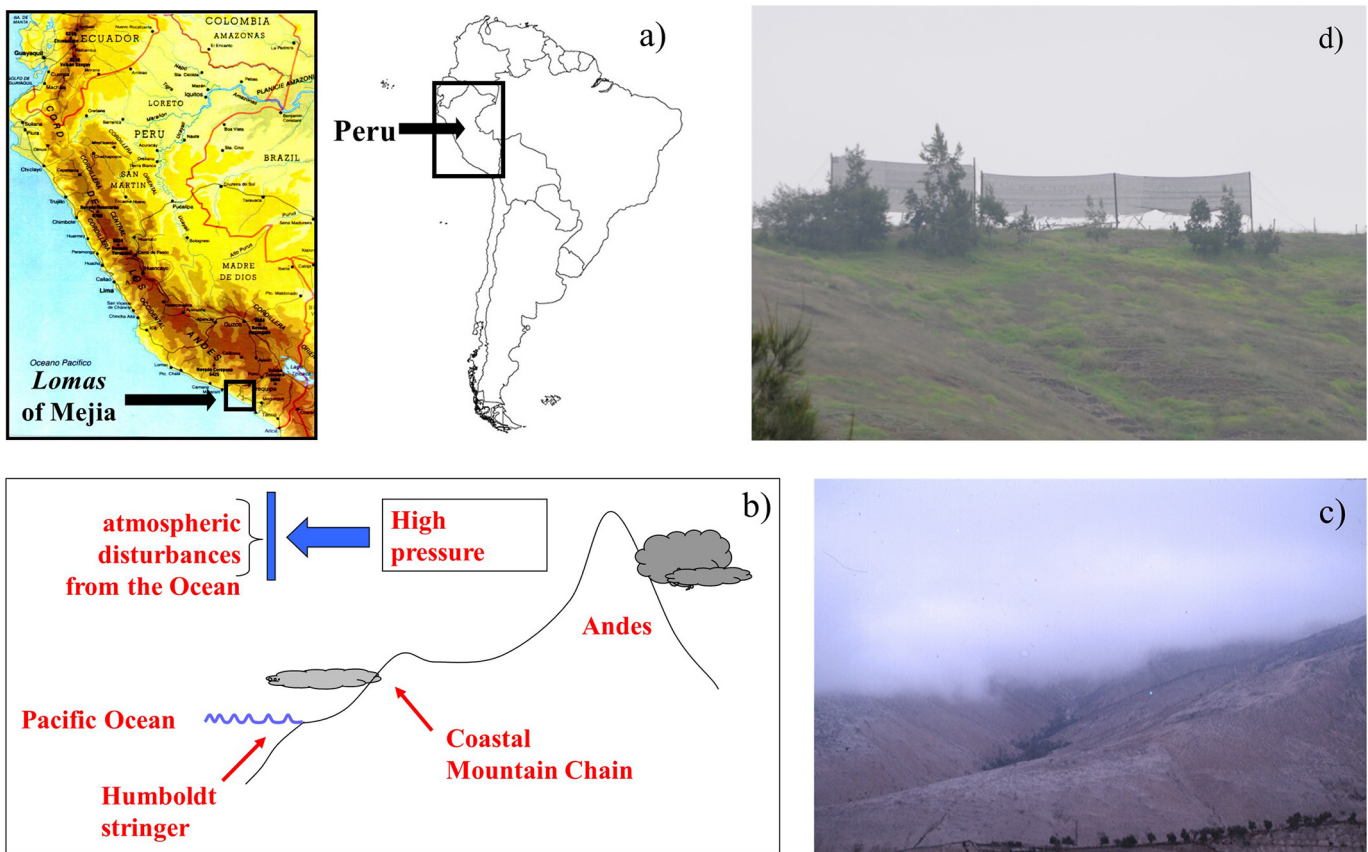

Fig. 1. a) Location of the study area in Peru (left) and Peru in South America; b) sketch showing the mechanisms causing the advection fog involving the lomas (W in the left-hand side of the sketch, E in the right-hand side); c) fog rising from the ocean to the ridge of the lomas of Mejia in the late afternoon; d) fog-harvesting nets placed at the study site (photo taken from W to E).
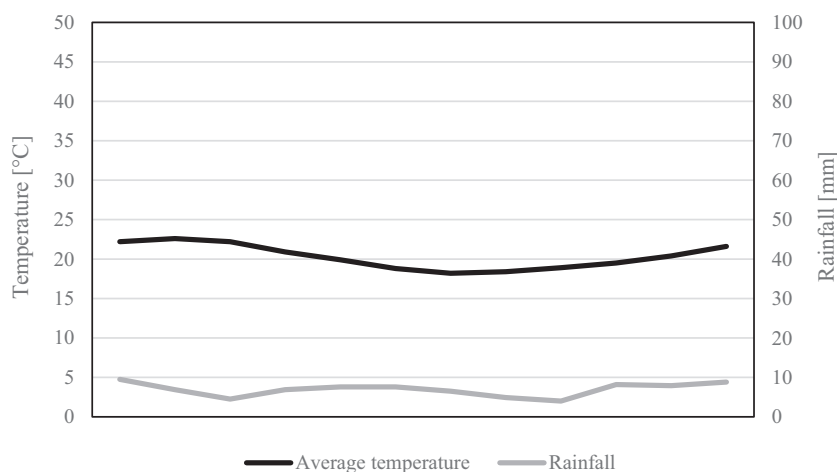
Fig. 2. Standardised climate diagram for Cocachacra weather station (Weatherbase, 2018).

droplets merge and altogether end up in tanks, to be used for irrigation or other purposes (Schemenauer et al., 2005). The pilot project "*Fog as a new water resource for a sustainable development of the Peruvian and Chilean Coastal Desert*", funded by the EU from 1995 to 1998, aimed at checking reforestation opportunities in barren *lomas* by supporting the first stage of tree growth with the water captured from fog flows by polyethylene nets (Semenzato et al., 1998). The main experimental site of the project was located at the *lomas* of Mejia, southern Peru (Fig. 1.a).

These are uplands experiencing an aridic type of climate, hence usually barren and ephemerally covered by herbaceous vegetation when abundant precipitations are brought by the ocean-warming phenomenon *El Niño*, which occurs approximately each 5–7 years. Some water arrives daily, rising as fog from the sea because of the adiabatic cooling effect of air masses (Fig. 1.b, c). However, most of such fog is lost to the atmosphere via evaporation. *Caesalpinia spinosa* (locally known as "Tara") trees, as single individuals or small groups, in savannah-like ecosystems or forming low density woodlands (60 to 120 trees/ha), are the remains of the presumably higher forest cover of the past, dramatically reduced by former and present logging and/or overgrazing. These tree formations are particularly able to use the water contained in fog and bring it down to the soil (Péfaur, 1982). Although foci for human activity in the past centuries, nowadays the surviving lomas are few and in southern Peru only the one in Atiquipa supports a substantial stand of forest (Balaguer et al., 2011).
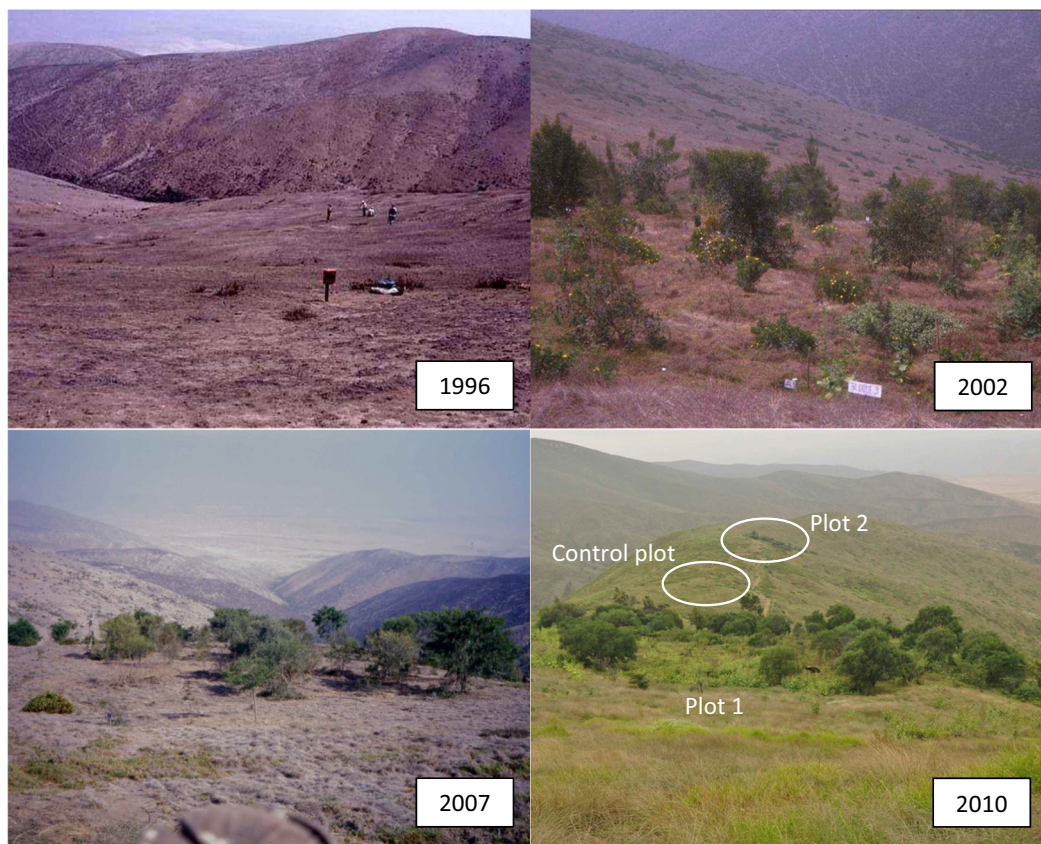

Fig. 3. A temporal sequence of pictures of the afforested plot T1, since the plantation to the last survey (1996–2010).
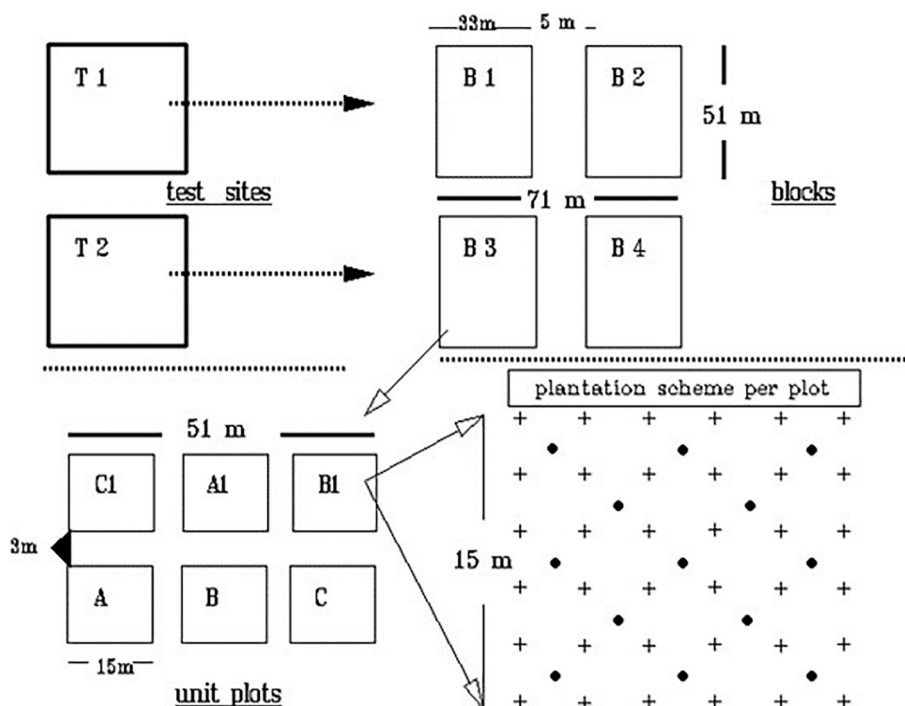
Fig. 4. Experimental design (+ indicating trees and · indicating shrubs).

In 1996, in Mejia, a series of 4-m high Raschel mesh nets was set in 1996 on top of the so-called "Las Cuchillas" ridge, to capture fog (Fig. 1.d) and use the so collected water for irrigating trees planted in two plots according to an experiment designed to test the response of different tree species and watering cycles. In 1999, i.e. three years after planting, the irrigation was stopped; hence, the plants had to rely on their own capacity of intercepting and using fog water.

This paper deals with the outcome of the experiment fourteen years since its beginning, mainly in terms of carbon (C) sequestration in the biomass and soil. It is known, in fact, that one of the most promising strategies to brake the greenhouse effect and mitigate climate change is to store as much as possible carbon dioxide in terrestrial or marine ecosystems. Photosynthesis removes C from the atmosphere, and may guarantee long residence times out of it, especially when the biomasses are sequestered and eventually transformed to recalcitrant forms in soils and sediments. Soils are the second C sink on Earth, soil organic carbon (SOC) globally amounting to about 1500 Pg C (Lal, 2004). Enrichment of soils in carbon implies better aggregation of soil particles and, consequently, higher porosity and resistance of soil to aeolian and water erosion. Desert soils are highly prone to erosion just because they are among the poorest ones in organic C. The factors promoting soil organic matter accumulation in soil are many, the first of which being the occurrence of substantial inputs. Crucial for this purpose is also the mineralogical assemblage; in fact, some minerals are more effective than others in binding SOC, so preventing its fast decay, which would imply return of C to the atmosphere as CO_2. Volcanic ejecta comprises many minerals particularly able to bind organics because of their scarce crystallinity (Ugolini and Dahlgren, 2002). Thus, desert volcanic

soils have a huge potential to store C if they undergo afforestation. However, the latter is possible in limited areas that guarantee sufficient water supply. This is the case of the study site described in this paper, where tree growth in two mixed-species stands was supported the first three years with water collected harvesting fog by big nets. Here, we present the outcome of the experiment, fourteen years since plantation, in terms of: i) survival rate, height, root-collar diameter, and biomass of trees; ii) amount of C and N stored in soil (intended as both the surface organic horizon and the underlying 10 cm of mineral soil) and the tree stands.

2. Materials and methods

The study area is located between 17° 00′ 00″ S and 17° 00′ 45″S and between 71° 59′ 50″ W and 71° 59′ 30″W in the Deán Valdivia district, Islay province, approximately 170 km from Arequipa in southern Peru (Fig. 1a).

The experimental site, Las Cuchillas ridge, about 10 km from the small-town of Mejia, is about 800 m above sea level. The mean annual precipitation in Cocachacra (the closest station, 17 km SE), is 83.3 mm (Weatherbase, 2018) and the mean monthly temperature range from 18.2 and 22.6 °C (Fig. 2).

According to Climate-Data.org algorithm (Climate-Data.org, 2018), the average climate features of Mejia (1,5 km absolute distance from the study area), are modelled[1] as a desert one. During the year very little rainfall occurs, with 20 mm/y of annual average in a 30 years period. Mejia can then be classified as BWn Desert climate with frequent fog according to Köppen and Geiger climate classification, as updated by Peel et al. (2007).

The geomorphology and soils of the study area are described in Calderoni et al. (2002). According to these authors, the soil of the afforested plots and the area in between left to the natural evolution is

Table 1
Dry wood density of the analysed tree species.

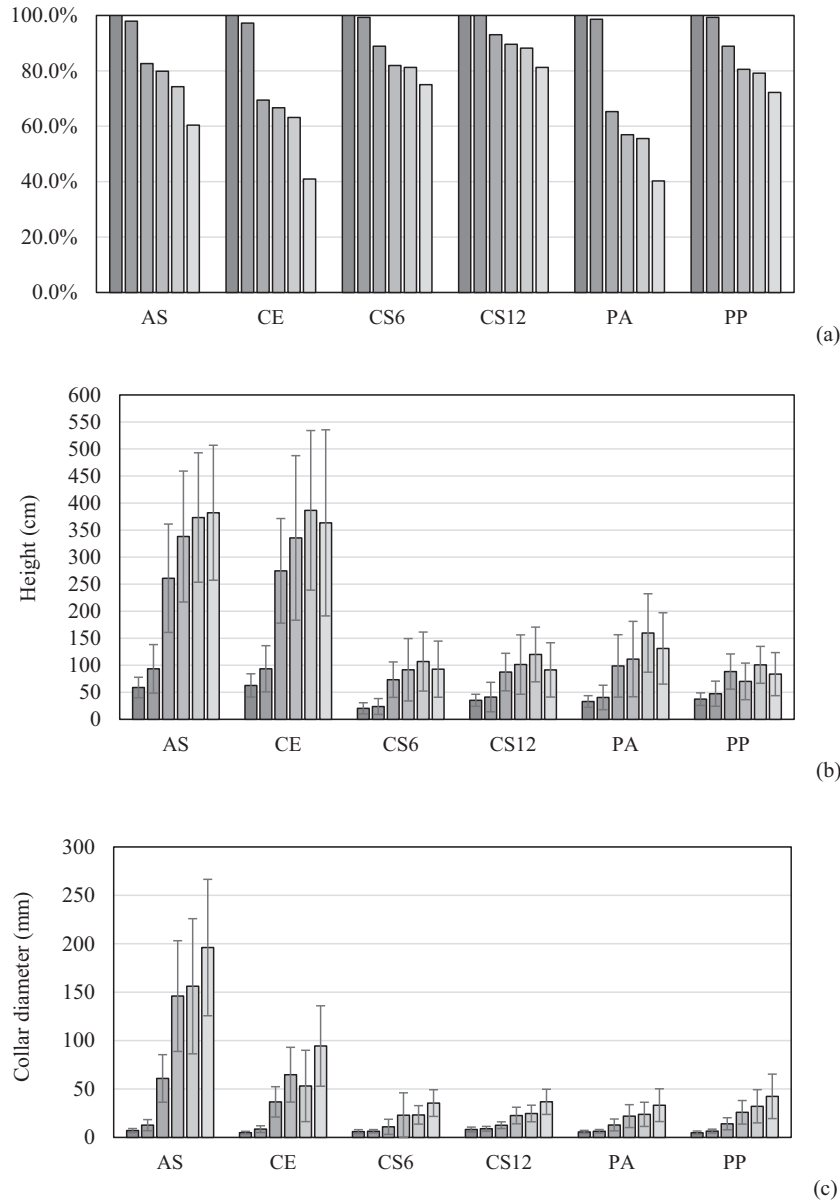| Tree species	Wood density [kg m^{-3}]	Source
Caesalpinia spinosa	1050	ICRAF, 2018
Prosopis pallida	880	Chave et al., 2009
Acacia saligna	600	Marcar et al., 1995
Casuarina equisetifolia	758	Chave et al., 2009
Parkinsonia aculeata	516	Chave et al., 2009

Fig. 5. Percentage (a), height (cm) (b) and root-collar diameter (mm) (c) of alive individuals across the two experimental plots (T1 and T2). Histograms from left to right represent year 1996, 1997, 1999, 2002, 2007, 2010. Black bars in 5.b and 5.c represents the standard deviation of the samples of alive individuals.

a *Vitrandic Haplargid* of the U.S. Soil Taxonomy (Soil Survey Staff, 2014), which shows an A/Bw/Btb sequence of horizons lying on the about 1 m deep granodiorite/gneiss bedrock of the pre-Cambrian basement. The A and Bw horizons developed on pyroclastic, mostly vitreous material emitted a few centuries ago by one or more of the several nearby volca- noes (e.g., the Huaynaputina or the Misti) and experienced weak pedo- genesis, while the deeper Btb horizon can be interpreted as part of a palaeosol developed over the crystalline bedrock and successively enriched in clay translocated from the superimposed material. The acid (pH around 5) and sandy-loam topsoil in the afforested plots was evidently enriched in organic matter (A horizon) and even showed a surface organic horizon elsewhere missing (except under the few scattered tufts of *Grindelia glutinosa*, which are the only green emer- gence in the long dry periods, along with some trees of *Caesalpinia*

Table 2
Percentage on the total and actual number (in parentheses) of alive individuals for T1 and T2.

	1996		1997		1999		2002		2007		2010	
	T1	T2	T1	T2	T1	T2	T1	T2	T1	T2	T1	T2
Acacia saligna	100% (72)	100% (72)	97% (70)	99% (71)	75% (54)	90% (65)	74% (53)	86% (62)	74% (53)	75% (54)	57% (41)	64% (46)
Casuarina equisetifolia	100% (72)	100% (72)	97% (70)	97% (70)	69% (50)	69% (50)	67% (48)	67% (48)	65% (47)	61% (44)	35% (25)	47% (34)
Caesalpinia spinosa 6 months	100% (72)	100% (72)	100% (72)	99% (71)	82% (59)	96% (69)	79% (57)	85% (61)	78% (56)	85% (61)	71% (51)	79% (57)
Caesalpinia spinosa 12 months	100% (72)	100% (72)	100% (72)	100% (72)	92% (66)	94% (68)	92% (66)	88% (63)	90% (65)	86% (62)	83% (60)	79% (57)
Parkinsonia aculeata	100% (72)	100% (72)	97% (70)	100% (72)	63% (45)	68% (49)	51% (37)	63% (45)	51% (37)	60% (43)	42% (30)	39% (28)
Prosopis pallida	100% (72)	100% (72)	99% (71)	100% (72)	83% (60)	94% (68)	81% (58)	81% (58)	81% (58)	78% (56)	74% (53)	71% (51)

Table 3
Average height and standard deviation (in parentheses) of alive individuals for T1 and T2 [cm].

	1996		1997		1999		2002		2007		2010	
	T1	T2	T1	T2	T1	T2	T1	T2	T1	T2	T1	T2
Acacia saligna	58 (21)	60 (16)	90 (44)	96 (46)	261 (100)	261 (101)	355 (119)	324 (122)	373 (132)	373 (107)	394 (142)	371 (108)
Casuarina equisetifolia	65 (23)	60 (20)	90 (41)	97 (45)	243 (76)	307 (105)	315 (155)	357 (148)	367 (158)	407 (134)	438 (175)	309 (150)
Caesalpinia spinosa 6 months	22 (11)	19 (10)	24 (17)	23 (11)	72 (35)	74 (31)	108 (66)	77 (44)	119 (66)	95 (39)	109 (65)	78 (30)
Caesalpinia spinosa 12 months	35 (11)	36 (12)	41 (35)	41 (16)	79 (35)	96 (33)	110 (60)	92 (48)	126 (60)	113 (38)	106 (57)	76 (36)
Parkinsonia aculeata	34 (11)	32 (11)	35 (17)	46 (26)	73 (35)	122 (64)	103 (62)	119 (75)	145 (65)	172 (77)	139 (69)	123 (63)
Prosopis pallida	36 (12)	39 (11)	44 (25)	51 (21)	84 (33)	92 (32)	72 (35)	69 (33)	103 (38)	98 (30)	96 (44)	71 (31)

Table 4
Average root-collar diameter and standard deviation (in parentheses) of alive individuals [mm] for T1 and T2.

	1996		1997		1999		2002		2007		2010	
	T1	T2	T1	T2	T1	T2	T1	T2	T1	T2	T1	T2
Acacia saligna	7 (2)	7 (2)	13 (6)	13 (5)	63 (25)	59 (24)	159 (62)	135 (50)	159 (72)	153 (68)	206 (81)	187 (59)
Casuarina equisetifolia	5 (1)	5 (1)	8 (3)	9 (4)	32 (14)	42 (16)	62 (32)	68 (24)	56 (46)	50 (24)	108 (52)	85 (29)
Caesalpinia spinosa 6 months	6 (2)	6 (2)	6 (2)	6 (2)	11 (3)	11 (10)	29 (32)	18 (7)	27 (11)	20 (7)	42 (12)	30 (13)
Caesalpinia spinosa 12 months	8 (2)	9 (2)	9 (2)	9 (3)	12 (3)	13 (4)	25 (10)	20 (7)	27 (10)	22 (6)	40 (14)	34 (11)
Parkinsonia aculeata	6 (1)	6 (1)	7 (2)	6 (2)	10 (3)	15 (7)	21 (11)	22 (13)	24 (13)	24 (12)	34 (18)	33 (16)
Prosopis pallida	5 (1)	5 (1)	6 (2)	7 (2)	13 (6)	15 (6)	27 (13)	24 (11)	35 (20)	30 (13)	49 (26)	35 (17)

spinosa, the sole tree species naturally present in the study area). At the beginning of this project, the soil contained about 1% in weight of organic C in the top 10 cm (Calderoni et al., 2002), which is the soil thickness we investigated.

Twenty large fog collectors (LFC) in polyethylene Raschel mesh (as in Schemenauer et al., 2005) had been placed in 1996 in the ridgeline of Las Cuchillas at 850 m a.s.l. Each LFC was 12 m wide and 4 m high, for a total area of 960 m², supported by wooden poles 7 m high and 12 cm in diameter. A PVC pipe (10 cm in diameter), cut in half lengthwise, was used to collect the water falling from the mesh. The collected water was stored in reservoirs and then used to irrigate the planted trees. In particular, the hydraulic network for storing and distributing water to the afforestation trials consisted of two reservoirs, one located nearby the fog collectors and the second one 100 m a.s.l. below, near the experimental plots, which were through drip irrigation pipes. The system was entirely gravity-fed.

An area of 42.000 m² surrounding the test site was fenced to avoid external disturbances. The ground of the test sites was prepared by ripping. Between June and July 1996, at the earliest fog season, 864 trees were planted according to a random-block design. The blocks were located in two different test sites (T1 and T2) with a difference in altitude of about 50 m. Four blocks were created and then divided into 6 plots. In each plot, 36 trees were planted, at a relative distance of 3 m, in each plot. Tree species were randomly placed in the frame of the plot. Five

species were selected for the experiment, two exotic – *Acacia saligna* (AS) and *Causarina equisetifolia* (CE) –; two are native *Prosopis pallida* (PP), and *Caesalpinia spinosa* (CS), and one is an introduced but naturalized species– *Parkinsonia aculeata* (PA),. The trees of *Caesalpinia spinosa* were double so to test two cohorts of seedlings (6 and 12 months old). The planting stock was prepared in nearby nurseries, i.e. Mollendo and Ilo. The seedlings have been sowed in single-tree polyethylene containers using a substrate 58% soil, 40% sand, 2% organic fertilizers. The tree stock was checked after 6 months and then the selected seedlings were transported to the field tree nursery prepared at the experimental station of Las Cuchillas. Here, the seedlings have been kept for the remaining months to planting, shaded by a 50% raschel-knit shade net and manually watered with 1 l fog-water daily.

To check the response of seedlings to water supply, 3 different time spans of irrigation were tested. In the first weeks after planting, all trees were supplied with 1 l water per day. Standard plastic tree shelters were placed to test the effect of microclimate on survival rate, establishment and growth.

The trees in the experimental plots underwent six different treatments:

- Treatment a – irrigation for 3 years after planting,
- Treatment a1 – irrigation for 3 years after planting and shelter
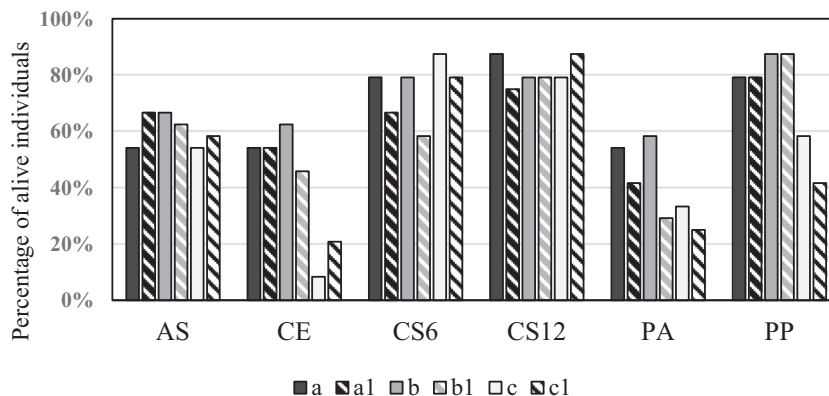- Treatment b – irrigation for 2 years after planting,

Fig. 6. Percentage of alive individuals per treatment in 2010. Treatments: (a) irrigation for 3 years after planting; (a1) irrigation for 3 years after planting and shelter; (b) irrigation for 2 years after planting; (b1) irrigation for 2 years after planting and shelter; (c) no irrigation; (c1) no irrigation and with shelter.

Fig. 7. Height of alive individuals per treatment in 2010. Treatments: (a) irrigation for 3 years after planting; (a1) irrigation for 3 years after planting and shelter; (b) irrigation for 2 years after planting; (b1) irrigation for 2 years after planting and shelter; (c) no irrigation; (c1) no irrigation and with shelter.
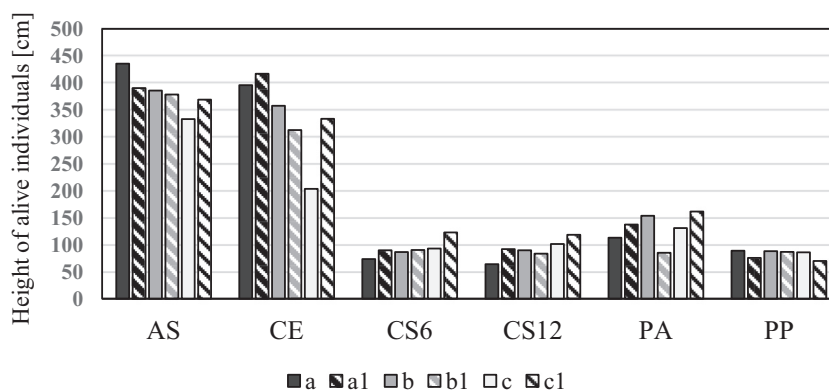
- Treatment b1 – irrigation for 2 years after planting and shelter
- Treatment c – no irrigation
- Treatment c1 – no irrigation and with shelter

Some images of the study area during the monitoring period are reported in Fig. 3, while the full experimental design in Mejia is shown in Fig. 4.

Tree growth dynamics was monitored over a period of 14 years, until 2010. Trees were measured in terms of survival rate, height and root-collar diameter in 1996, 1999, 2002, 2007, and 2010, identifying the root-collar diameter as the diameter measured at the transition zone between the root and the stem, particularly visible in seedling and checked by visual inspection.

Carbon stored in trees was calculated with the following formula:

$$C = \pi^{cd^2}\Big/_4\, h\, d\, f$$

where C is the carbon mass stored in the tree stem in kg, cd is the root-collar diameter in m, h is the tree height in m, d is the wood density of the species – expressed as kg of dry matter on fresh volume (see Table 1) – and f is the fraction of C on the total, as estimated by Thomas and Martin (2012). In practice, the shape of a young tree stem was approximated to a cylinder.

During the last session of measurements, in 2010, the stocks of C and N sequestered in soil were determined in the two afforested plots and a non-forested one in between (Fig. 3). Fifty-two spots located at intervals of 1.5 m on north south and east west oriented perpendicularly-crossing transects (26 samples per transect) were sampled. Where present – mostly under the crowns of *Acacia saligna* – the litter layer was sampled by collecting all the material within a 20×20 cm squared frame, down to the contact with the mineral soil. Since a preliminary survey had shown that most of the pedogenic organic matter was actually confined to the uppermost centimetres in all spots, the top 10 cm of mineral soil was sampled, on a volume basis by a still cylinder of known volume (152 cm³) to determine the bulk density. The litter layer and the top mineral soil were oven-dried (60 °C) to constant weight, and the second was also passed through a 2-mm mesh sieve to remove rock fragments. A representative aliquot of both were finely ground by a ball-mill and analysed for total C and N by a Perkin-Elmer CHN Analyzer 2400 Series 2. Total C could confidently be considered all in organic form, due to the acid reaction of the soil, which is incompatible with the presence of carbonates. Carbon and nitrogen concentrations (kg Mg^{-1}) for the mineral soil were finally reported on a surface basis (kg m^{-2}) using the bulk density data.

To evaluate the persistence of the forest cover up to present days, a canopy cover assessment was performed by the *i-Tree canopy* tool (2009) on Google Maps aerial photographs to conduct a cover assessment within the study area. Two rectangles of 0.5 ha each, comprising respectively T1 and T2 plots, were drawn based on Google map imagery dated 03/09/2018. Eighty random points were generated by i-Tree canopy and each one classified as Tree/Non-tree. Afterwards, the .kml files were extracted and imported in Google Earth Pro.

The survey was repeated with historical imagery using the point cloud previously generated. In particular, two images were selected,
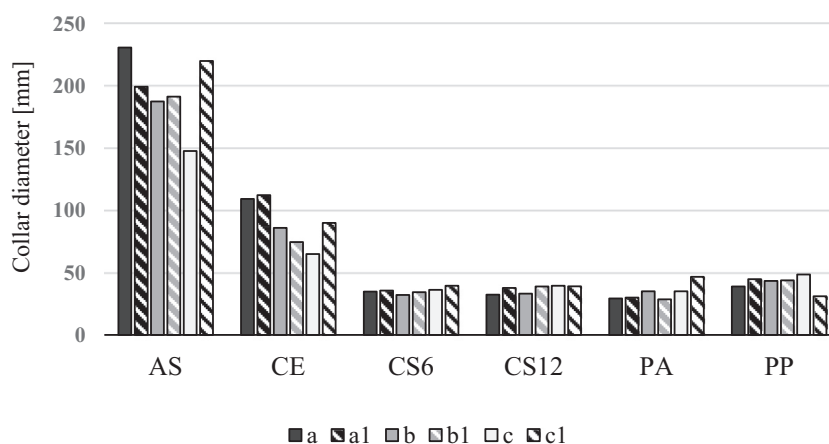

Fig. 8. Root-collar diameter per treatment in 2010. Treatments: (a) irrigation for 3 years after planting; (a1) irrigation for 3 years after planting and shelter; (b) irrigation for 2 years after planting; (b1) irrigation for 2 years after planting and shelter; (c) no irrigation; (c1) no irrigation and with shelter.

Table 5
Estimation of average (standard deviation) and total values of carbon stock in trees in different years of survey [kg C].

Species		1996	1997	1999	2002	2007	2010
AS	Average	0.01	0.05	3.09	22.3	28.2	42.5
		(0.01)	(0.06)	(2.61)	(20.0)	(26.9)	(38.5)
	Total	1.14	7.00	367	2560	3010	3700
CE	Average	0.01	0.03	1.52	6.26	5.11	15.0
		(0.00)	(0.03)	(1.44)	(7.82)	(9.08)	(25.5)
	Total	0.75	3.81	152	601	465	871
CS6	Average	0.00	0.00	0.04	0.57	0.35	0.64
		(0.00)	(0.00)	(0.06)	(3.15)	(0.50)	(0.75)
	Total	0.52	0.68	5.61	66.8	40.8	68.6
CS12	Average	0.01	0.02	0.07	0.31	0.39	0.67
		(0.01)	(0.02)	(0.05)	(0.46)	(0.49)	(1.04)
	Total	1.63	2.27	8.91	40.3	49.8	78.2
PT	Average	0.00	0.00	0.05	0.21	0.29	0.49
		(0.00)	(0.00)	(0.08)	(0.34)	(0.43)	(0.89)
	Total	0.34	0.55	5.13	17.1	23.6	28.5
PP	Average	0.00	0.01	0.08	0.25	0.56	0.91
		(0.00)	(0.01)	(0.08)	(0.39)	(1.04)	(1.92)
	Total	0.49	1.17	10.2	29.6	63.5	94.1

the ones of 23/04/2003 and 31/03/2013, based on their high visual quality, absence of clouds, and acceptable time range to discriminate tree cover changes. To compare the encroachment of the experimental plot to the surrounding landscape, a Wider project Area (WA) of 100 ha was designed and the i-Tree survey was repeated by generating 100 random points.

3. Results and discussion

3.1. Survival rate, height and root-collar diameter

Monitoring alive seedlings (out of the initial 864 individual trees) revealed how the CS seedlings 6 months old (CS6) and 12 months old (CS12), and the PP ones adapted well to site conditions, with survival rates of 75%, 81% and 72%, respectively (Fig. 5.a). However, in spite of lower survival rates (60% and 41%, respectively), AS and CE showed the best growth rates (Fig. 5.b and c).

The AS trees showed consistent wooden volumes, as inferred from the root-collar diameters. The CE trees grew in height like the AS ones, although with lower volumes, given by the smaller diameter. The aggregated data revealed that CE was the species with the second lowest survival rate. On the other hand, the very high survival rate of both CS6 and CS12 cohorts actually demonstrates that *Caesalpinia spinosa* deserves consideration to be used for fog-fed reforestation, here and elsewhere.

In 2010, the two plots showed similar survival rates (Tables 2 to 4), although a bit higher in T2 for AS and CE. Plant size was higher in T1 for all species, especially AS and CE. Again in 2010, in both T1 and T2, AS had average tree heights of 3.94 m and 3.71 m, respectively, while CE had heights of 4.38 m and 3.09 m. Looking at the root-collar diameter, AS showed the highest values, on average 206 mm in T1 and 187 mm in T2, while CE showed diameters of 108 mm in T1 and 85 mm in T2. PA, which counted few survived individuals (<40%), however showed not negligible height and root-collar diameter values, i.e. 1.31 m and 33 mm over the two plots.
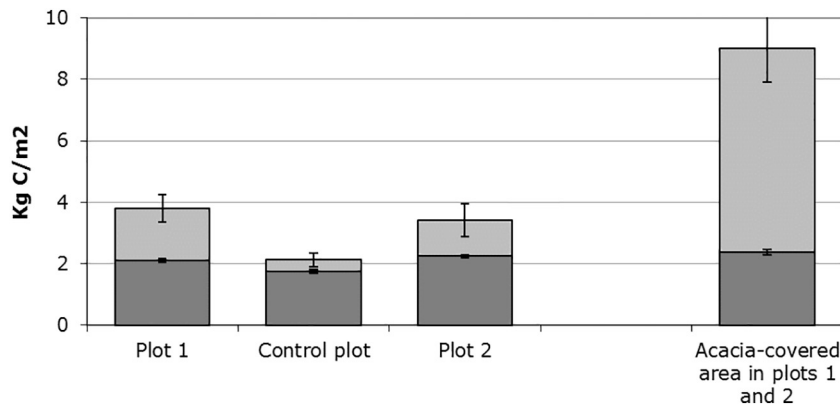

Fig. 9. Carbon stocks (error bars are the standard deviation) in the organic horizon (light grey perched columns) and the top 10 cm of mineral soil (dark grey basal columns) of the two afforested plots, the control area in between, and the *Acacia*-covered area only in T1 and T2.

Fig. 10. Nitrogen stocks (error bars are the standard deviation of mean) in the organic horizon (light grey perched columns) and the top 10 cm of mineral soil (dark grey basal columns) of the two afforested plots, the control area in between, and the *Acacia*-covered area only in T1 and T2.
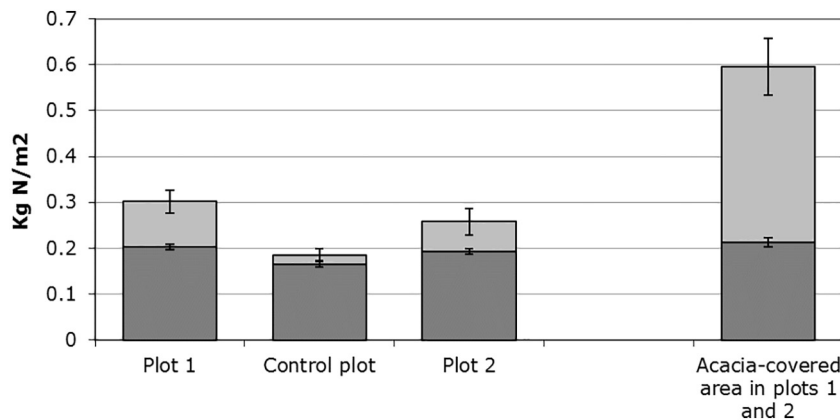
Table 6
Average of C and N stocks (in parentheses the standard deviation) in the organic horizon and the top 10 cm of mineral soil of the two afforested plots, the control area in between, and the *Acacia*-covered area only in T1 and T2. Differences between means are indicated by different superscript letters.

	C in the organic horizon [kg/m²]	C in the top 10 cm of mineral soil [kg/m²]	N in the organic horizon [kg/m²]	N in the top 10 cm of mineral soil [kg/m²]
T1 1 (n = 52)	1.690 (0.435)[a]	2.108 (0.052)	0.100 (0.026)[a]	0.202 (0.006)
Control plot (n = 52)	0.390 (0.223)[b]	1.743 (0.059)	0.021 (0.012)[b]	0.065 (0.030)
T2 (n = 52)	1.178 (0.535)[abc]	2.240 (0.052)	0.065 (0.030)[abc]	0.193 (0.005)
Acacia-covered area in plots T1 + T2 (n = 21)	6.637 (1.092)[c]	2.364 (0.089)	0.383 (0.062)[c]	0.213 (0.009)

Disaggregated data (per treatment) related to the last monitoring are reported in Figs. 6, 7 and 8. There were no significant changes in terms of survival between the irrigated (a, a1, b and b1) and non-irrigated parcels (c and c1) for all the species analysed but CE. For CE, in fact, the lack of irrigation was fatal, being the average survival rate just 15% in the non-irrigated parcels vs. about 54% in the irrigated ones. Fig. 6 shows also that, for non-irrigated cohorts, shelters increased the survival rate for AS, CS12 and especially for CE.

3.2. Carbon stock in trees

The carbon stock in trees expectedly increased with time (Table 5). In the last survey, most of C was confined in AS and CE, the first species on average storing 42.5 kg per plant and the latter 15.0 kg per plant, for total stocks of 3.70 Mg and 0.87 Mg, respectively. As a term of comparison, in Acacia plantations in Indonesia, i.e. under tropical climate with an average rainfall of 2660 mm y^{-1}, Kalita et al. (2016) measured an average stock of around 90 kg per plant, which is just twice the value observed in Meija. Hence, the growth rate of AS at our study site is not negligible, at all, taking into account the climatic limitations they have to face.

3.3. Carbon and nitrogen stocks in soil

The tree-covered soil showed more C and N than the non-forested one (Figs. 9 and 10, and Table 6), therefore afforestation supported by initial irrigation (especially considering its role for the development of CE) was actually efficient in promoting both soil C and N sequestration.

Most C and N had accumulated in the top organic horizon (comprising a thick little decomposed litter layer overlying a thinner layer of moderately decomposed residues) under the crowns of AS, while the other tree species contributed little or not at all in this regard, because of their high mortality (especially CE and PA) and/or reduced growth rate (especially CS, PA, and PP). As well as under all AS trees, we found the organic horizon only in a couple of cases under PA and two other cases under CT in T1. The T1 plot had significantly more C in the organic horizon than the other afforested plot, T2. Such a discrepancy could be mainly explained by the different number of sampled spots located under the canopy of AS (13 in T1 vs. 8 in T2) and – at a lesser extent – by the higher growth of AS and CE in T1. In the non-forested plot, the organic horizon was much less frequent, having been found only in three of the fifty-two sampling points, in correspondence with turfs of the grass *Grindelia glutinosa* of the *Asteraceae* family. AS is clearly the main driving factor of litter accumulation, so much that if one plot was afforested with just this species, it would have theoretically shown four to five times the carbon allocated in the organic horizon of

the two current afforested plots (Table 6). The same differences found for C more or less occurred for N, despite AS is a N-fixer species and a higher differential between the afforested plots and the control could be expected for this element.

No significant differences between the two afforested plots or between them and the control were found in the mineral soil in terms of both C and N (t-test at a 95% confidence level). Even comparing the control with just the samples collected under the canopy of AS from both T1 and T2, we did not find any significant difference, which means that the C and N enrichment occurred on the ground did not (yet) involve the mineral soil, as expected with time passing (Paul et al., 2002; Lal, 2005).

3.4. Persistence of forest cover

The estimated tree cover of the experimental plots increased decisively from 2003 to 2018 (Table 7), with a slight prevalence in T2 than in T1, the statistical significance of the difference is significant with p-value < 0.0001 in all cases (confidence >99%). This variable is substantially greater in the two plots than in WA, where the values are around 4 to 5% with very little changes on time.

These results show how the canopy cover persisted from the end of the experiment (2010) up to present days (2018), despite the fact that no more conservation interventions have been after 2010.

4. Conclusions

The experimentation of fog-fed afforestation carried out at Las Cuchillas ridge in Southern Peru fourteen years after its start can be considered successful, since in such a relatively short period it allowed producing biomass, providing a habitat suitable to birds and a plethora of other wildlife, feeding grazers, protecting the barren ground from erosion, and promoting significant C and N sequestration in soil (although confined to the uppermost part of it and in rather labile forms). Moreover, the elaboration of satellite remote sensing images showed the persistence and even expansion of the generated forest cover in time, up to present days.

Therefore, this experience could be plausibly repeated here and in other similar fog-affected arid environments, with some modifications suggested by this work. In particular, future plantations should rely on a higher *Acacia saligna* contribution than the one adopted for the experiment, since among the tree species *Acacia* was the only one that grew satisfactorily. Additionally, this species succeeded in forming a thick forest floor, rich in nitrogen and partly humified, which has obvious positive ramifications in terms of soil quality and climate change mitigation. Irrigation, realised with fog water collected by the system of 20 LFC, was found to be not fundamental for *A. saligna* development. However, it was for the second most relevant species monitored, i.e. *Casuarina equisetifolia*, and moreover to water all the seedlings before the planting. *A. saligna*, along with the local *Caesalpinia spinosa*, has good potential as natural fog collector since the transplanting, supporting also the development of ground level vegetation and biodiversity. Taking into account other positive properties – such as early reproductive maturity, copious dispersal, quick ability of seeds to germinate after cutting or burning, extensive root system, high growth rates – *Acacia saligna* represents a species to rely on for the reforestation of fog-affected areas of Atacama Desert, at least in the first phase of

Table 7
Evolution of forest cover (%) in the study area for the selected image dates. Averages of the values in the selected sampling points, with standard deviations in parentheses.

Image date	23/4/2003	31/3/2013	3/9/2018
T1	52.6 (5.65)	57.0 (5.57)	62.8 (5.47)
T2	57.1 (5.91)	64.3 (5.73)	70.0 (5.48)
WA	4.3 (2.61)	4.6 (2.47)	4.9 (2.24)
p-value on T1 and T2 difference	p < 0.0001	p < 0.0001	p < 0.0001

reconstitution of the forest. Later, it could be partially and progressively substituted by other more demanding species, possibly the local ones, such as *Caesalpinia. spinosa,* which showed high survival rates despite relatively slow growth, and considering supplemental irrigation with fog-collected water.

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