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The enhancing effect of afforestation over secondary succession on soil quality under semiarid climate conditions

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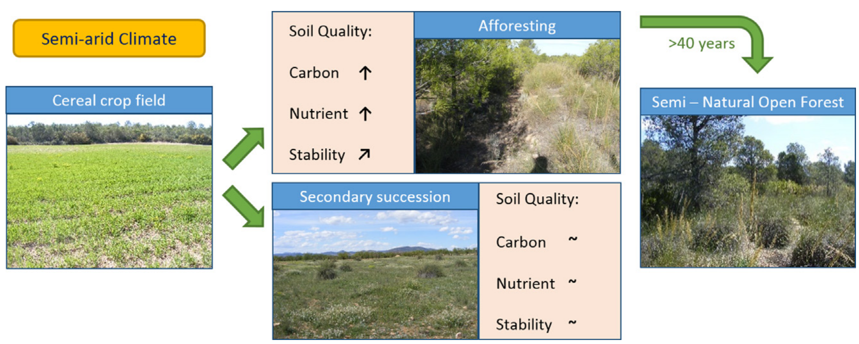
HIGHLIGHTS

- Secondary succession caused soil degradation during the first 20 years.
- Afforesting improved most studied soil quality indicators.
- Natural resource islands were formed by afforesting after 40 years.

GRAPHICAL ABSTRACT



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ABSTRACT

Semiarid climate conditions hamper natural re-vegetation, leaving the soil vulnerable to erosion after the cessation of agriculture. Therefore, soil and landscape protective measures, especially afforestations, have been implemented in the Mediterranean region since the early 20th century. This study aims to determine the long term impact of afforestation on soil functioning, in comparison with natural re-vegetation (secondary succession) on abandoned fields and semi-natural vegetation.

A comparison of secondary succession and afforestation with the present traditional rain fed cereal fields and semi-natural (open) forest, including natural resource islands, was made as well. Composite soil samples were taken to study the physical (i.e. texture, aggregate stability) and chemical (i.e. carbon content, nutrient availability) soil characteristics after 20 and 40 years of afforestation and secondary natural succession. To take into account the resource island effect, the spatial heterogeneity induced by differences in plant cover, samples were taken both below and in between the tree canopy of the semi-natural and afforested *Pinus halepensis* trees.

Our results indicate that under secondary succession on abandoned fields, soil quality improves non-linearly and only marginally over a time of 40 years. The afforestation showed a much more pronounced linear increase for most soil quality indicators, resulting in soil conditions comparable to what can be found under the semi-natural forest vegetation. Site preparation might have been a crucial factor for the success of ecosystem restoration in the studied dry land area as it improved water availability for the afforestation.

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1. Introduction

Since the 19th Century, cropland abandonment has been a predominant form of land use change in the European Mediterranean landscape. Due to different economic and social reasons, more and more land became and will become abandoned in the (European) Mediterranean area (García-Ruiz, 2010; García-Ruiz and Lana-Renault, 2011; Lasanta et al., 2017). Under semiarid Mediterranean climate and less favourable soil conditions this process is hampered, and thus the bare soil remains prone to degradation (Geeson et al., 2003; Romero-Díaz et al., 2017). Together with the typical highly variable inter-annual rainfall amounts and intensities in this region, this leads to a considerable loss of fertile soil (Bracken et al., 2008; Martínez-Mena et al., 2001).

The practice of planting late-succession species has been implemented for reducing the amount of erosion and overland flow on bare and degraded lands. For instance, since the beginning of the 20th century the practice of afforesting abandoned and degraded rangelands has been conducted on the Iberian Peninsula (Ortigosa et al., 1990; Vallejo, 2005), but is also implemented in other dryland areas in the world such as the Chinese Loess plateau, Central USA and in the Mediterranean climate region of Australia (Hoogmoed et al., 2012; Zhang et al., 2013). Afforestation has been primarily seen as land degradation mitigation measure, but the focus shifted towards carbon storage and soil rehabilitation in the last decades (Muñoz-Rojas et al., 2011; Zhang et al., 2018).

Soil quality is a widely used term to describe the proper functioning of the soil and is mostly expressed by studying its (individual) indicators soil organic carbon (SOC) or soil organic matter (SOM) (Armenise et al., 2013; Masto et al., 2008). SOC and SOM correlates well with soil hydrological functioning (Mataix-Solera et al., 2007; Rawls et al., 2003) and structural stability (Keesstra et al., 2018; Van Hall et al., 2017) and is an important part of the global carbon cycle (Lal, 2012). The C:N:P stoichiometry is a comprehensive indicator of soil nutrient status and the imbalance of elements induced by vegetation growth/succession (Zhang et al., 2018). Aggregate stability of soil macro-aggregates is recognized as an important indicator on the capability of the soil to resist against erosional forces (Cammeraat and Imeson, 1998).

The effectiveness of afforesting abandoned agricultural fields and degraded rangelands under (semi-) arid condition as a soil restoration measure is still an important point of discussion (Cortina et al., 2011; García-Franco et al., 2014; Maestre and Cortina, 2004; Ruiz-Navarro et al., 2009). However, a comparison with secondary succession has hardly been made in these discussions. As mentioned earlier, secondary succession is mostly hampered under semiarid climate conditions. This means that vegetation composition and cover develops non-linearly over time. Subsequently, soil quality develops also non-linearly, whereby substantial setbacks can occur over time (Bonet, 2004; Lesschen et al., 2008; Lozano et al., 2014). It is therefore important to understand the non-linear behaviour of the ecosystem dynamics to improve the decision making of when and where to invest in restoration measures (Sietz et al., 2017).

This paper aims to contribute to the "usefulness discussion" on investments in afforestation as a re-greening measure in dryland ecosystems, from a soil quality perspective, in particularly when secondary succession is considered as an alternative. The main research question to be answered was: How does soil quality changes after afforestation or secondary succession on the decadal timescale? Considering the observations of the previously discussed studies, it was hypothesized that secondary succession might result only in minor changes, while afforestation has the potential to have a larger impact on soil quality over the studied timespan. To study the potential enhancing effect by afforestation on soil quality, soils under different Land Use Histories (hereafter, LUH) in a relative homogenous landscape are evaluated.

2. Materials and methods

2.1. Study area

In order to study the effect of LUH on soil quality, a field study has been performed in the northern part of the Guadalentín river

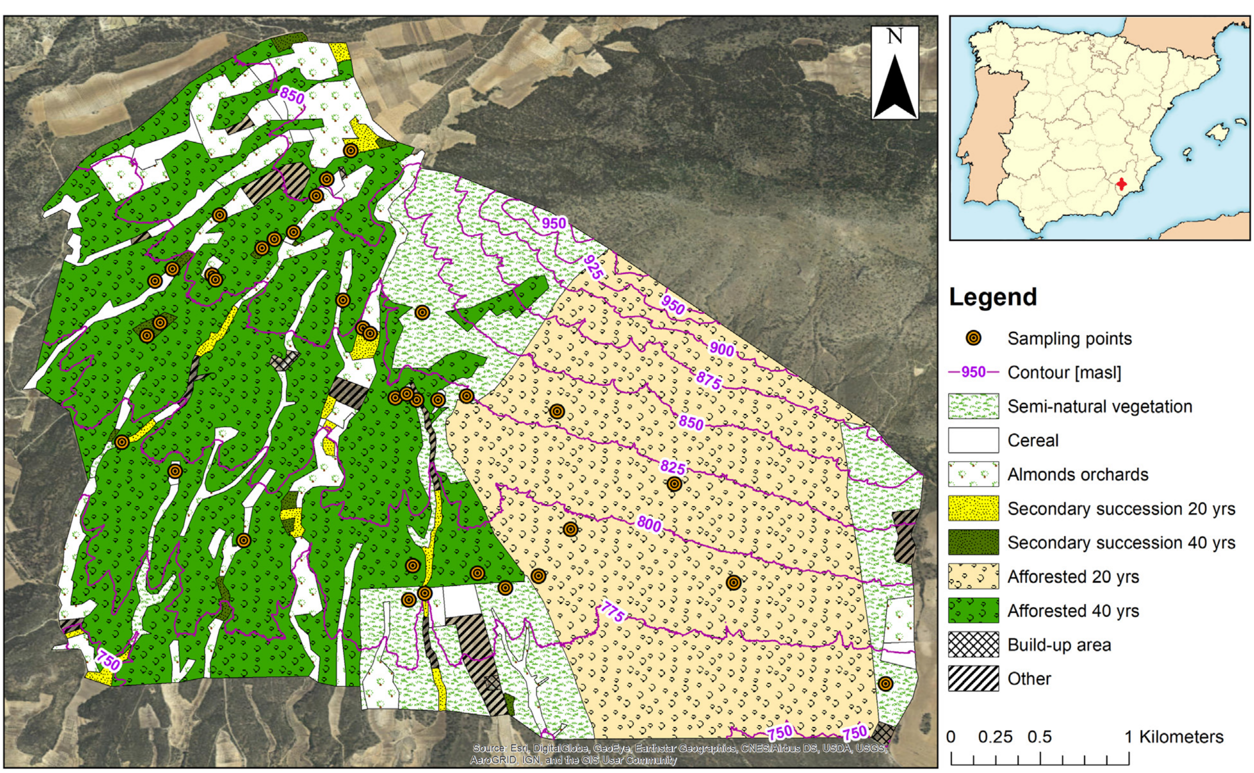

Fig. 1. Land Use History of the research area, obtained by interpretation of air photos of different years. Red dot on upper right map indicate the location of the study area on the Iberian Peninsula. Created using ArcGIS (ESRI).

Table 1
Means per Land Use History, five replicates per LUH, of the studied soil properties. Standard deviation is shown in brackets. a and b indicate significant different grouping between LUH classes.

		Cereal	20 yr Sec. succession	40 yr Sec. succession	20 yr afforested open	40 yr afforested open	Semi-natural open	20 yr afforested canopy	40 yr afforested canopy	Semi-natural canopy
Sand	[%]	39 (8)	26 (7)	35 (8)	33 (3)	39 (8)	42 (10)	35 (5)	40 (10)	40 (8)
Silt	[%]	46 (6)	55 (6)	48 (4)	49 (3)	44 (5)	43 (6)	48 (5)	45 (7)	44 (6)
Clay	[%]	15 (3)	19 (1)	17 (5)	18 (2)	17 (4)	15 (5)	17 (3)	15 (4)	16 (2)
pH	[−]	7.97 (0.17) a	7.87 (0.12) ab	7.85 (0.05) ab	7.76 (0.07) ab	7.73 (0.10) ab	7.72 (0.07) ab	7.65 (0.09) b	7.62 (0.16) b	7.70 (0.25) ab
EC	[μS cm^{-1}]	252 (75) a	264 (37) ab	288 (25) ab	313 (31) ab	319 (53) ab	319 (33) ab	367 (56) ab	435 (128) b	430 (59) b
Bulk density	[g cm^{-3}]	1.09 (0.05) a	1.02 (0.07) ab	1.05 (0.10) ab	0.86 (0.06) ab	0.93 (0.12) ab	0.87 (0.20) ab	0.90 (0.09) ab	0.89 (0.22) ab	0.75 (0.18) b
Aggregate stab.	[#]	30 (21) a	44 (21) ab	48 (26) ab	41 (13) ab	85 (52) ab	97 (22) b	88 (61) ab	73 (49) ab	120 (30) b
SOM	[g kg $soil^{-1}$]	27.5 (8.3) a	26.5 (9.9) ab	38.6 (4.6) ab	56.1 (6.1) ab	57.3 (11.2) ab	58.1 (5.9) ab	67.8 (31.8) ab	83.5 (28.2) b	83.1 (18.5) b
C-tot.	[g kg $soil^{-1}$]	82.5 (12.5)	79.8 (7.2)	82.9 (14.1)	82.2 (9.3)	84.2 (14.3)	91.6 (15.0)	94.8 (11.1)	104.9 (19.4)	101.7 (15.2)
C-inorg.	[g kg $soil^{-1}$]	63.4 (7.1)	65.2 (5.2)	62.4 (13.3)	51.1 (6.9)	51.8 (12.8)	54.8 (19.9)	50.4 (13.1)	52.6 (11.4)	46.3 (12.9)
C-org.	[g kg $soil^{-1}$]	19.1 (8.3) a	14.6 (5.5) ab	20.5 (5.3) ab	31.2 (4.2) ab	32.4 (4.6) ab	36.7 (7.1) ab	44.4 (16.6) ab	52.3 (25.0) b	55.3 (4.6) b
N-tot.	[g kg $soil^{-1}$]	1.32 (0.37) a	1.34 (0.43) ab	1.74 (0.28) ab	2.53 (0.25) ab	2.46 (0.24) ab	2.40 (0.22) ab	2.70 (0.33) b	3.24 (1.01) b	3.10 (0.41) b
P-tot.	[g kg $soil^{-1}$]	0.28 (0.06)	0.29 (0.02)	0.31 (0.06)	0.26 (0.03)	0.24 (0.02)	0.24 (0.03)	0.27 (0.03)	0.31 (0.04)	0.26 (0.03)
P-inorg.	[g kg $soil^{-1}$]	0.12 (0.03) a	0.14 (0.02) ab	0.14 (0.05) ab	0.08 (0.01) ab	0.07 (0.01) ab	0.12 (0.05) ab	0.12 (0.06) ab	0.07 (0.02) ab	0.06 (0.02) b
P-org.	[g kg $soil^{-1}$]	0.16 (0.04)	0.14 (0.03)	0.17 (0.03)	0.19 (0.03)	0.18 (0.02)	0.12 (0.05)	0.15 (0.05)	0.24 (0.05)	0.19 (0.02)
K	[mg kg $soil^{-1}$]	28.82 (19.98)	28.78 (22.24)	28.77 (25.71)	18.80 (4.45)	21.55 (3.88)	26.41 (9.91)	32.08 (13.77)	37.73 (11.42)	44.82 (18.71)
Na	[mg kg $soil^{-1}$]	7.96 (1.79) a	10.72 (4.25) ab	12.14 (4.44) ab	12.05 (3.79) ab	11.28 (2.03) ab	9.25 (1.12) ab	14.12 (4.72) ab	19.89 (9.39) b	23.83 (8.47) b
Fe	[mg kg $soil^{-1}$]	0.30 (0.06) a	0.43 (0.18) ab	0.32 (0.08) ab	0.27 (0.02) ab	0.34 (0.13) ab	0.36 (0.07) ab	0.34 (0.11) ab	0.61 (0.48) ab	0.70 (0.29) b
Al	[mg kg $soil^{-1}$]	0.66 (0.15)	0.74 (0.31)	0.67 (0.20)	0.47 (0.05)	0.59 (0.19)	0.66 (0.33)	0.53 (0.14)	0.57 (0.14)	0.76 (0.23)
Ca	[mg kg $soil^{-1}$]	227.0 (34.6) a	231.8 (32.5) ab	265.8 (25.6) ab	321.2 (27.7) ab	329.6 (42.9) ab	312.4 (40.6) ab	367.1 (58.7) b	427.5 (143.8) b	389.6 (61.8) b
Mg	[mg kg $soil^{-1}$]	12.83 (2.71) a	17.44 (3.02) ab	14.63 (3.43) ab	13.75 (2.21) ab	17.16 (4.70) ab	16.02 (3.38) ab	18.39 (4.33) ab	42.77 (31.26) b	33.64 (12.75) b
Mn	[μg kg $soil^{-1}$]	22.9 (6.5)	22.8 (9.3)	19.7 (5.3)	21.6 (10.4)	20.5 (6.5)	18.3 (6.4)	24.2 (3.2)	55.0 (55.5)	43.7 (22.9)
S-tot.	[g kg $soil^{-1}$]	0.35 (0.06) a	0.31 (0.10) ab	0.35 (0.04) ab	0.43 (0.05) ab	0.39 (0.03) ab	0.41 (0.04) ab	0.45 (0.05) ab	0.51 (0.15) ab	0.52 (0.11) b
C-org./N-tot.	[−]	11.2 (0.9)[1] a	10.8 (1.4) ab	11.9 (3.1) ab	12.3 (0.8) ab	13.2 (1.7) ab	15.3 (2.1) ab	16.1 (4.5) ab	15.7 (2.1) ab	18.1 (2.8) b
C-org./P-tot.	[−]	71.4 (41.0) a	50.2 (15.4) ab	66.4 (11.0) ab	119.1 (20.3) ab	133.0 (18.4) ab	154.1 (29.9) ab	165.0 (56.5) b	164.7 (61.5) b	218.6 (44.7) b
N-tot./P-tot.	[−]	4.7 (0.8) a	4.6 (1.2) ab	5.7 (1.2) ab	9.7 (1.4) ab	10.1 (0.4) b	10.0 (0.7) b	10.1 (1.7) b	10.3 (2.2) ab	12.2 (2.4) b

Note: SOM, Soil Organic Matter; C-tot., Total Carbon content; C-inorg., Inorganic Carbon content; C-org., Organic Carbon content; N-tot., Total Nitrogen content; S-tot., Total Sulphur content; P-tot., Total Phosphorus content; P-inorg., Inorganic Phosphorus content; P-org., Organic Phosphorus content. Elements K, Na, Fe, AL, Mg, Ca and Mn are the water soluble amounts (see methods).

[#] Average amount of drops needed to disrupt an aggregate.

[1] Outlier of a value 33.5 excluded

Table 2
χ^2 and resulting p-value of the Kruskal-Wallis one-way analysis of variance of the individual soil properties over the different Land Use History classes, consisting of five replicates per LUH. Values in italic are significantly different.

	Sand	Silt	Clay	pH	EC	Bulk density	Aggregate stability	SOM	C-tot.	C-inorg.	C-org.	N-tot.	P-tot.
χ^2	11.6	13.5	8.9	19.8	25.4	18.0	24.3	33.0	14.9	12.3	34.4	35.7	14.0
p-value	0.170	0.095	0.353	*0.011*	*0.001*	*0.021*	*0.002*	*0.000*	0.060	0.140	*0.000*	*0.000*	0.082

	P-inorg.	P-org.	K	Na	Fe	Al	Ca	Mg	Mn	S	C-org./N-tot.	C-org./P-tot.	N-tot./P-tot.
χ^2	26.1	16.4	10.5	24.5	17.9	10.1	33.6	27.4	12.9	23.0	23.3	32.3	32.0
p-value	*0.001*	*0.037*	0.230	*0.002*	*0.022*	0.261	*0.000*	*0.001*	0.116	*0.003*	*0.003*	*0.000*	*0.000*

Note: EC, Electrical Conductivity; SOM, Soil Organic Matter; C-tot., Total Carbon content; C-inorg., Inorganic Carbon content; C-org., Organic Carbon content; N-tot., Total Nitrogen content; S-tot., Total Sulphur content; P-tot., Total Phosphorus content; P-inorg., Inorganic Phosphorus content; P-org., Organic Phosphorus content.

catchment in southeastern Spain. The climate in the area is semiarid Mediterranean, with a dry period from May till September. Annual average temperature is about 18 °C and annual precipitation 300 mm (Meteorological station Embalse de Puentes). On the homogenous surface of a pediment, gently sloping southward from the Sierra del Madroño (37°53′N 1°45′W), two afforestation projects were conducted on parts of the pediment in the mid 1970's and in 1993 (Fig. 1). In the study area a Petric Calcisols (IUSS Working Group WRB, 2014) developed from a limestone rich substrate. For the afforestation the calcrete, following the land surface at a depth of ~25 cm, was cracked open with a bulldozer or tractor to create furrows using a subsoiler, in which the *Pinus halepensis* tree seedlings were planted. Benches were created from the remaining soil, which were planted with the grass species *Macrochloa tenacissima*. These two species are widely used in re-vegetation projects in the arid and semiarid areas in the Mediterranean basin, but also dominate the semi-natural vegetation (Pausas et al., 2004; Vallejo, 2005).

Table 3
Results of principal component analysis (PCA) of soil properties for the first six Principal Components (PC). The most important parameters per PC, with highest loadings ±10%, are highlighted.

Principal components	PC1	PC2	PC3	PC4	PC5	PC6
Eigenvalue	12.02	3.54	2.69	1.85	1.20	1.00
Variance percent	46.2	13.6	10.4	7.1	4.6	3.9
Cumulative var. perc.	46	60	70	77	82	86
Eigen vectors						
Sand	0.075	**−0.483**	0.126	−0.015	−0.028	−0.023
Silt	−0.102	**0.430**	−0.085	−0.011	0.070	0.090
Clay	−0.001	0.424	−0.163	0.058	−0.058	−0.108
pH	−0.218	0.049	0.064	0.206	−0.011	0.341
EC	**0.269**	0.010	0.061	−0.080	−0.080	−0.094
Bulk density	−0.188	−0.091	0.216	−0.052	−0.217	0.000
Aggregate stab.	0.152	−0.019	−0.084	0.031	**0.383**	−0.275
SOM	**0.268**	0.005	−0.060	−0.032	−0.041	−0.056
C-tot.	0.218	−0.234	0.190	−0.071	0.046	0.132
C-inorg.	−0.102	−0.254	0.283	−0.293	**0.378**	0.084
C-org.	**0.266**	−0.018	−0.042	0.154	−0.238	0.054
N-tot.	**0.270**	0.054	−0.122	−0.048	−0.107	−0.128
P-tot.	0.013	0.236	**0.361**	−0.277	**−0.410**	−0.167
P-inorg.	−0.139	0.080	0.319	0.261	−0.113	**−0.476**
P-org.	0.142	0.135	0.023	**−0.490**	−0.259	0.296
K	0.149	−0.041	**0.387**	0.010	−0.039	−0.300
Na	0.218	0.155	0.068	−0.043	0.247	0.175
Fe	0.210	0.202	0.244	0.114	0.247	0.178
Al	0.015	0.175	0.335	0.434	0.150	0.060
Ca	**0.268**	0.005	−0.039	−0.056	−0.044	−0.093
Mg	0.240	0.113	0.211	−0.053	0.089	0.159
Mn	0.222	0.161	0.219	0.033	0.117	0.186
S	**0.254**	0.028	−0.015	0.002	0.002	−0.147
C/N-ratio	0.115	−0.181	0.054	0.407	**−0.375**	0.348
C/P-ratio	**0.249**	−0.115	−0.150	0.245	−0.109	0.033
N/P-ratio	**0.244**	−0.073	−0.272	0.068	0.078	−0.148

Note: EC, Electrical Conductivity; SOM, Soil Organic Matter; C-tot., Total Carbon content; C-inorg., Inorganic Carbon content; C-org., Organic Carbon content; N-tot., Total Nitrogen content; S-tot., Total Sulphur content; P-tot., Total Phosphorus content; P-inorg., Inorganic Phosphorus content; P-org., Organic Phosphorus content.

A mosaic of land uses, with traditional rain fed cereal crop fields, abandoned fields and semi-natural vegetation, is present in the study area. Air photographs from 1945, 1956, 1981, 1997 and 2013 were used to determine the site history, which were checked during the sampling in April 2015 (Fig. 1). These images were freely available from the regional government of Murcia (http://iderm.imida.es/cartomur/, last accessed April 2017).

The crop fields are mechanically ploughed with a cultivator on a regular base and mainly cereal crop species are grown during the wetter periods. Some fields were for unknown reason abandoned and left unattached, except for small scale herding occurring in the area. The open forest vegetation was classified as semi-natural, as orthophotos showed no change in canopy cover since 1945, but human influences in the form of herding and small scale pruning could not be excluded. Furthermore, the age of afforestation/forest stand was confirmed using a wood increment borer, taken into account that a few dry years created no tree ring (Moreno-Gutiérrez et al. 2012).

The vegetation composition of afforestations and semi-natural open forest is dominated by *Pinus halepensis* trees, the legumes shrubs *Anthyllis cytisoides*, the shrub *Rosmarinus officinalis* and the *Macrochloa tenacissima* grass species, whereby the shrubs were less abundant in the afforestations. Furthermore, *Quercus coccifera* shrub could mainly be found as undergrowth under the *Pinus halepensis* trees in the semi-natural vegetation. The semi-natural vegetation consists of a patchy vegetation cover, forming so-called resource islands in which many soil quality indicators are enhanced (Bochet et al. 1999).

The sparse vegetation on abandoned fields were dominated by (annual) grass and herbal species, although small shrub species, i.e. *Helianthemum almeriense*, are also present. Especially after 40 years of secondary succession the first *Macrochloa tenacissima* grass tussocks and more shrub species, like *Thymus vulgaris* and *Rosmarinus officinalis*, could be found.

2.2. Sampling strategy

During a sampling campaign in April 2015, 5 plots per LUH were chosen depending on representability of the area and the disconnectivity between them. On each of these plots composite soil samples were taken by gently mixing 5 subsamples per plot. Each subsample was taken under the *Pinus halepensis* tree canopy using a steel cylinder, whereby the 5 most representative trees were chosen in a plot of 10 × 10 m. Adjacent to the sampled trees, in between the canopies of other plants, subsamples were taken to represent the open area of the same plot. On current used agricultural (cereal) and abandoned fields 5 subsamples were taken in an area of 10 by 10 m, in between canopy areas of perennial grass or shrub species. Before sampling, the litter of the ectorganic horizon was removed and the first 10 cm of the soil was sampled. Additionally, 100 cc sampling cores were taken to estimate bulk density. In the afforested and semi-natural plots, a distinction was made between the area covered by the tree canopy and open (intercanopy) area, whereby the open area samples are taken in the bare spots, where plant influence is at a minimum.

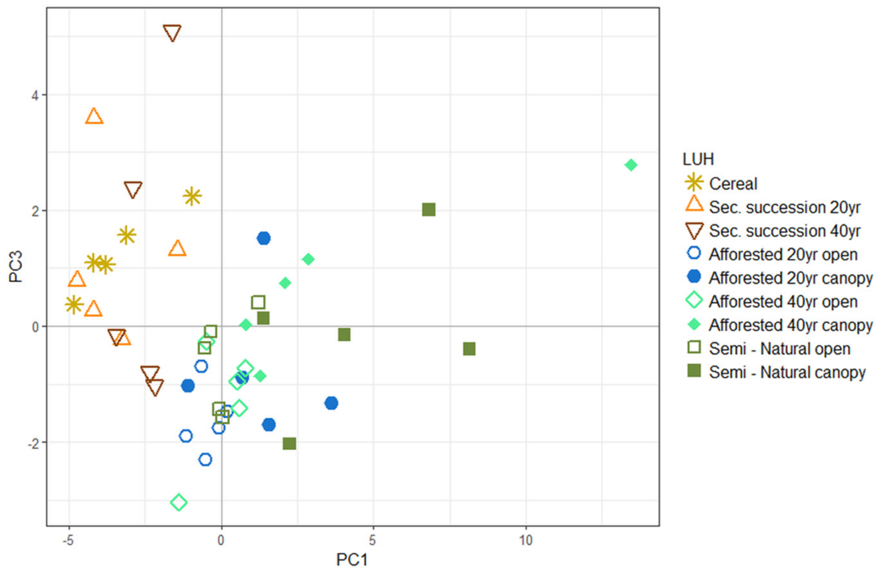

Fig. 2. Individual soil samples plotted on the first and third principal component axes.

2.3. Laboratory analysis

With a 2 mm mesh sieve, the fine earth fraction was obtained. The following soil parameters were determined in the laboratory: (I) Bulk density by drying 100 cc core samples at 105 °C (Blake and Hartge, 1986); (II) Soil texture, after oxidizing the organic material with peroxide, by wet sieving over 63 μm and silt + clay fraction further quantified by a Sedigraph (IIIplus, Micrometrics); (III) pH and electrical conductivity (EC), measured in a deionized water suspension (1:2.5), shaken overnight, using a standard pH and a conductivity meter; (IV) Total carbon (C-tot), total nitrogen (N-tot) and total sulphur (S) measured by dry combustion in a elementar analyser (Vario EL Cube Elementar); (V) Inorganic carbon (C-inorg) using the Wesemael method (Van Wesemael, 1955); (VI) Soil organic matter (SOM) by the loss-on-ignition method at 375 °C; (VII) Total and organic phosphorus (P-tot and P-org), determined through the difference in phosphorus in ignited (at 500 °C for 4 h) and non-ignited samples, by extraction with sulphuric acid (0.5 M) and using Molybdenum blue for the colorimetric method (Kuo, 1996); (VIII) Water extracts (1:10) were made over night, and the water available cations Aluminium (Al), Calcium (Ca), Iron (Fe), Magnesium (Mg), Manganese (Mn), Potassium (K) and Sodium (Na) measured by a ICP-OES (Perkin Elmer Optima 8000). Organic carbon (C-org) was calculated from the difference between C-tot and C-inorg. Furthermore, aggregate stability, of the size class 4–4.8 mm, was determined by the water drop impact method of Imeson and Vis (1984). Briefly, 20 aggregates per plot were pre-wetted till a pF of 1 on a sand-box before the actual test. The average amount of drops needed to disrupt the 20 aggregates was used as parameter, whereby a maximum of 200 drops was taken.

2.4. Statistical analysis

Data analysis was carried out with R, whereby the *stat* package was used if not mentioned otherwise (R Development Core Team 2017).

To identify the most important parameters describing changes in the soil after land use change, a Principal Component Analysis (PCA) was performed following the method of Armenise et al. (2013) and Masto et al. (2008). Principal Components (PCs) with eigen value ≥ 1 were examined further. The variables on these PCs with high factor loading are assumed to be most explanatory for expressing the changes in the soil, induced by land cover change. Furthermore, differences between LUHs, taking all studied parameters into account, were tested by a permutational multivariate analysis of variance (Per-MANOVA) from the *vegan* R-package (Oksanen et al., 2018). The same R-package was used for further visualization, using a hierarchical cluster created from the group means, using Euclidean distance and nearest neighbour.

The individual parameters were further examined on their distribution and differences between LUHs. As the assumption of normal distribution per factor level could not be met for most parameters, as checked by a Shapiro-Wilk normality test, the non-parametric Kruskal-Wallis one-way analysis was used to test variances between the site histories. To identify which LUHs statistically differ from each other, the multiple comparison test designed to conjunct with the Kruskal-Wallis test of the *pgirmess* R-package was used (Giraudoux, 2017). Correlations between parameters were checked and tested by the Spearman's rank correlation test.

3. Results

3.1. Identifying most important indicators

The dataset used for the PCA is summarized in Table 1, in which means and standard deviations per LUH are displayed. The letters indicate a statistical difference, as tested by the Kruskal-Wallis test, between LUHs, for which the $\chi2$- and p-value can be found in Table 2.

The PCA revealed that several soil parameters linked to the SOM content, like C-org and EC, determined the first PC (Table 3). The second PC was dominated by the three texture classes, it can be seen in Table 1 that there was not a significant difference between the different LUHs. The most important parameters on the third PC were P-tot and water available K (Table 3). As the explanatory power of the second and third hardly differ, 13.6% versus 10.4%, it was decided to use the third PC to plot the individual sampling points in Figs. 2 and 4. A plot using the second PC can be found in the supplementary material.

When the individual sampling points were plotted on the first and third PC, a relative clear grouping can be observed (Fig. 2). The secondary succession grouped with the cereal fields, while the open areas of both the afforestation and semi-natural vegetation forms a second group. An interesting observation is that the sampling points of the canopy areas show a much more heterogeneous pattern in the PCA plot (Fig. 2). The age of the trees seems to determine the distance from the centre of the plot, indicating that the studied parameters under the trees are further off from the overall average values, but not for all parameters the same.

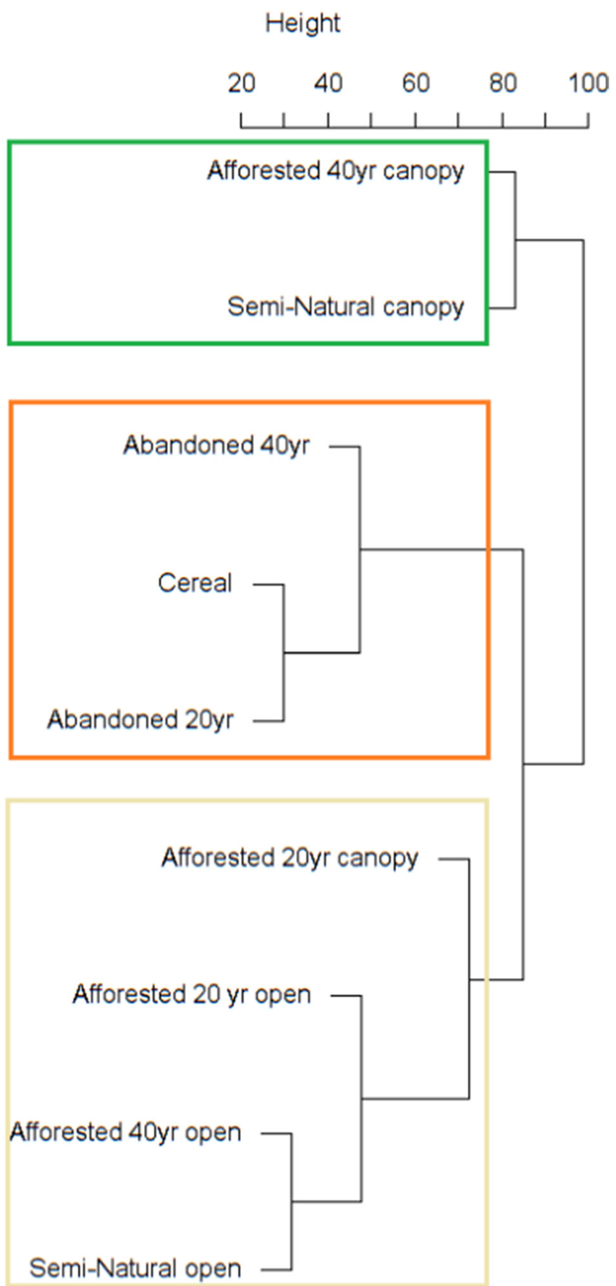

Fig. 3. Hierarchic clustering of the means of all studied parameters, grouped over the Land Use History, using Euclidean distance and nearest neighbour as settings.

Results of the Per-MANOVA test indicated that the LUHs differ from each other significantly ($p < 0.001$). To visualize these results, a dendrogram of group mean clusters was created and displayed in Fig. 3. It can be seen that especially the cereal and abandoned fields differ much from the other sites. The canopy sites of 40-year afforestation and semi-natural plots can be distinguished as a second group.

The fact that many studied soil parameters aligned with SOM (Fig. 4) and SOM had a high score on the first PC (Table 3), expresses the explanatory strength of SOM for distinguishing between the different LUHs. A range of parameters correlated with SOM, as indicated with the Spearman rank correlation tests (Fig. 5). In the correlogram of Fig. 5 all possible correlations between the individual parameters, independent of LUH, can be found and will be used further on to discuss the coherency between the individual parameters.

3.2. Accumulation of soil organic matter

As previously shown in the PCA, differences in SOM content are the strongest explanatory factors between the LUHs. In Fig. 6 it becomes clear that the SOM content between cereal field and the canopy area of the 40-year-old afforestation and semi-natural vegetation is significant different. Furthermore, it can be seen that 40 years of secondary succession was needed to increase the SOM content, but remained below what is found in the open areas.

Several other soil chemical and physical soil properties were associated with the increase in SOM, as can be seen in the correlogram (Fig. 5). Many nutrients, such as N-tot (ρ 0.91) and K (ρ 0.40), are significantly correlated to SOM content. Also changes in aggregate stability (ρ 0.50), C-inorg (ρ −0.40) and BD (ρ −0.52) can be related to differences in SOM content.

3.3. C:N:P stoichiometry

C-org/N-tot (C:N), C-org/P-tot (C:P) and N-tot/P-tot (N:P) ratios were calculated to gain a better insight into the relative changes of these nutrients. A clear difference in soil C:N:P stoichiometry is observed between the cereal fields/secondary succession and afforestation/semi-natural sites, as can be seen in Fig. 7. N-tot content increased over 40 years of succession, but as C-org increased as well, it resulted in a stable C:N ratio (Table 1). Under afforestation the C:N ratio increased, whereby the highest values were found under the semi-natural vegetation (Fig. 7a).

On the other hand, P-tot hardly changed, resulting in large difference between C:P and N:P ratios between the cereal fields/secondary succession and afforestation/natural sites. Ratios got lower due to higher P-tot levels on agricultural fields (Table 1). It can also be found in the correlogram (Fig. 5) that P-tot is not correlated to any other soil parameter besides the C:N and C:P ratios. Nonetheless, the ratios correlated very well with SOM content: resp. ρ-values of 0.76, 0.81 and 0.69 for C:P, N:P and C:N. Especially the high correlation coefficients with C-org. (0.95 and 0.91 for resp. C:P and C:N) shows direct connection between these soil parameters.

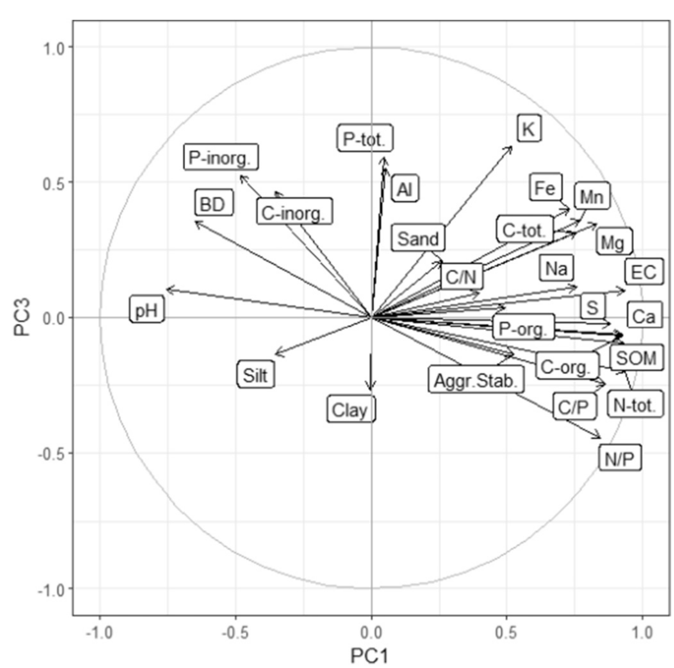

Fig. 4. Distribution of the individual parameters on the first and third principal components.

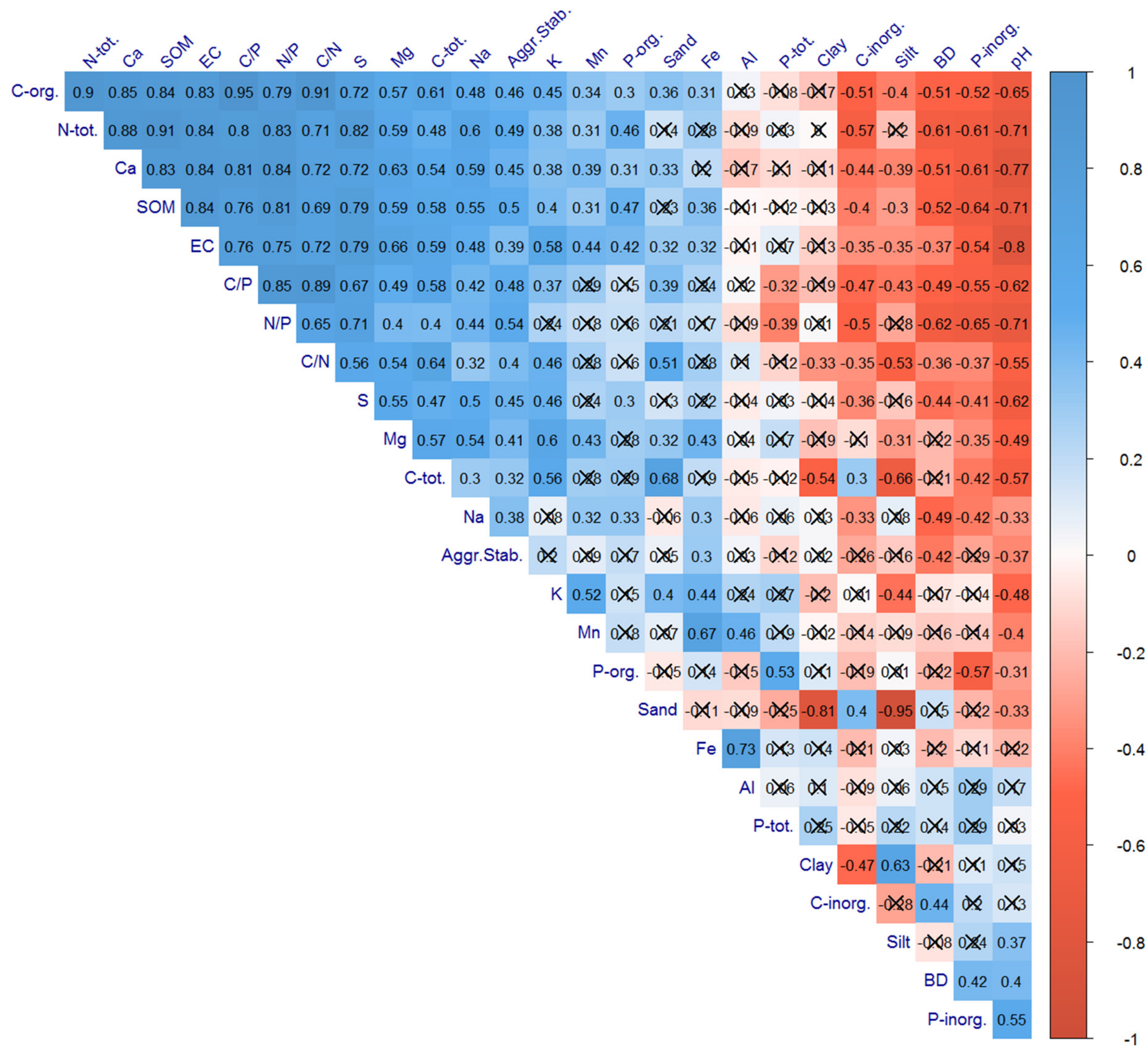

Fig. 5. Correlogram of the dataset, using the Spearman rank correlation test. Non-significant ($p > 0.05$) coefficients are crossed.

3.4. Aggregate stability

Aggregate stability is widely seen as an important soil quality indicator to describe soil structural stability. However, in this study aggregate stability turned out to be only dominant on the fifth PC, which explains 4.6% of the variance between LUHs (Table 3). As can be seen in Fig. 8, the aggregate stability showed a gradual increase for both secondary succession and afforestation, whereby the most stable aggregates can be found under the semi-natural canopy and in the semi-natural open area. Note also the large spreading in the 40-year-old afforestation. In the correlogram it can be seen that SOM had one of the largest correlations with aggregate stability (ρ 0.50), indicating the relative close relation between SOM content and aggregate stability.

4. Discussion

4.1. Secondary succession on abandoned fields

As the PCA and per-MANOVA analysis showed, secondary succession had no substantial effect on soil quality in general (Figs. 2 & 3). Nonetheless some interesting trends over time of secondary succession on abandoned fields can be observed. For instance, the SOM content slightly decreased during the first 20 years, while after 40 years a slight increase is observed (Fig. 6). Correspondingly C-org are also obtained a minimum after 20 years of secondary succession (Table 1). This trend is quite typical for secondary succession under semiarid climate conditions, as it is closely linked to the non-linear development of the vegetation, influencing the SOM input and quality (Bonet 2004; Lesschen et al., 2008; Lozano et al., 2014). The first stage of secondary succession is mainly dominated by herbaceous species, which seems not to establish a full soil cover or enhance soil fertility and has even been linked to higher erosion rates (Nunes et al., 2010). Gabarrón-Galeote et al. (2015) showed that after 20–30 years of secondary succession C-org stocks were lower than initially, under similar climate conditions as the current study area. In their study, C-org stocks recovered afterwards when the net primary production increased by changes in the vegetation composition (Gabarrón-Galeote et al., 2015). A similar trend is also observed, as SOM content slightly increased after 40 years (Fig. 6).

P-tot did not change much over time of secondary succession, having the most predominant impact on the C:N:P stoichiometry (Fig. 7 & Table 1). It has previously been demonstrated that the fertilizing effect of phosphorus on agricultural fields can persist for at least several decades (Cuesta et al., 2012; Nadal-Romero et al., 2016). The slight increase in C:P, N:P ratio and relative stable C:N ratio hints at a small phosphorus limitation (Zhang et al., 2018). Although comparing the N-tot and P-tot content to other studies, it does not appear that these nutrients are very limited (Cuesta et al., 2012; Nadal-Romero et al.,

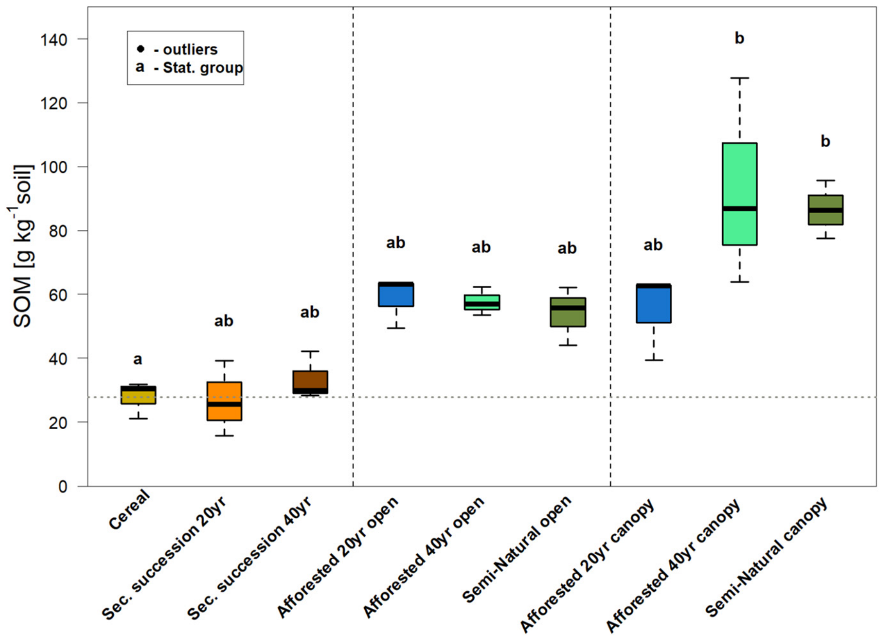

Fig. 6. Box-and-whisker diagrams showing the median (black line), 25th, 75th (resp. upper/lower part box) and min./max. Value (whiskers) for SOM content. The horizontal grey line represents the mean value found in the "Cereal field" plots.

2016; Ruiz-Navarro et al., 2009). It is more likely that the phosphorus is not bioavailable by the high pH of the soil (Deng et al., 2017). The stable C:N ratio over time of secondary succession (Fig. 7a) indicates a stable state between input and decomposition of organic matter after 40 years of secondary succession.

Vegetation generally increases SOM content and soil porosity, reducing bulk density and favouring a better environment to biological activity, which, together with the cessation of agricultural activities, enhances aggregate stability (Cerdà, 1998). On the other hand, the recovery of the soil microbial community after the cessation of agricultural practice can take several decades and has been related to reduction in recovery of the aggregate stability (Duchicela et al. 2012, 2013). This could explain the observed slight increase in aggregate stability over time of secondary succession (Fig. 8).

The stocks and changes of pedogenetic carbon (C-inorg) are underrepresented in studies on presence and changes in carbon stocks in soils, especially in (semi-) arid areas (Domingo et al., 2011; Monger et al., 2015). Furthermore inorganic carbon stocks in semi-arid regions are often much larger than organic carbon stocks, as in the current case. Although we only studied the upper part of the soil, this is also the place where changes are largest as a result of land use change and changes in impact by biota, soil formation, weathering and erosion processes. As can be seen in Table 1, the C-inorg content slightly increased, while bulk density decreased after secondary succession, indicating an accumulation of carbonates in the top soil. It can be hypothesized that when ploughing ceases, pore water can rise further upward as evaporation dominates, whereby also the carbonates precipitate higher in the soil column (Zamanian et al., 2016). As soil development is hampered and the plant cover changes over time, preferential flow path formation is inhibited and deeper percolation of infiltrating water does not occur before larger plant species develop (Cammeraat et al., 2010). Further research into C-inorg should go into mechanisms and rates of pedogenetic carbon formation, and natural and anthropogenic effects of pedogenetic carbon.

4.2. Afforestation on abandoned fields and degraded rangelands

40-year-old afforested and semi-natural canopy area turned out to have a different soil quality than the open areas and/or cereal fields in general. The PCA showed that age of the canopy cover is a determining factor, whereby the canopy plots of the 20-year-old afforestation closely related with the open areas (Fig. 2). This finding indicates that several decades are needed to form a natural heterogeneous soil quality pattern, the so-called resource islands (Bochet et al. 1999).

A substantial increase in SOM content could be observed under the canopy area of the afforestation, whereby differences between plots decreased over time since afforestation (Fig. 6). Probably the most interesting fact is that the SOM content under 40-year-old canopy area was similar to what was found under the semi-natural canopy and already differed significantly from the cereal fields (Table 1). Together with the accumulation of SOM under the canopy, many soil parameters improved (Table 1). The deeper rooting trees might act as a nutrient pump, whereby the litter forms a source of nutrients for the top soil (Pugnaire et al., 2011).

In cereal fields half the phosphorus is stored in organic matter, but under afforestation this increased to 75% (Table 1). It can be hypothesized that phosphorus stored in organic matter (P-org) is more easily available for the microbial and faunal communities in an ecosystem. Furthermore the constant N:P ratio indicated that these two nutrients are in balance (Fig. 7c) and does not form a limiting factor (Deng et al., 2017; Zhang et al., 2018).

Despite the fact that afforestation improved aggregate stability after 40 years, it still did not resemble the aggregate stability under the semi-natural vegetation (Fig. 8). As SOM content is relative similar between the 40-year-old afforestation and semi-natural vegetation (Fig. 6), it seems that aggregate stability is not solely depending on SOM quantity. It is well-known that the widely used *Pinus halepensis* tree species, which are planted in a relative dense pattern, capture a substantial amount of rainfall, through which the performance of understory shrub species is hampered (Pugnaire et al., 2011). This causes a difference in litter quality input between the afforestation and semi-natural vegetation. For example, the *Quercus coccifera* species occurs mainly in the (semi-)natural vegetation and is associated with an enhanced aggregate stability (Cerdà, 1998). However, Cammeraat and Imeson (1998) report significantly higher SOC and soil aggregation under isolated natural *Pinus halepensis* trees compared to other land uses in a nearby area. Previously Duchicela et al. (2013) and Zornoza et al. (2009a, 2009b) showed that the presence of fungi could be correlated

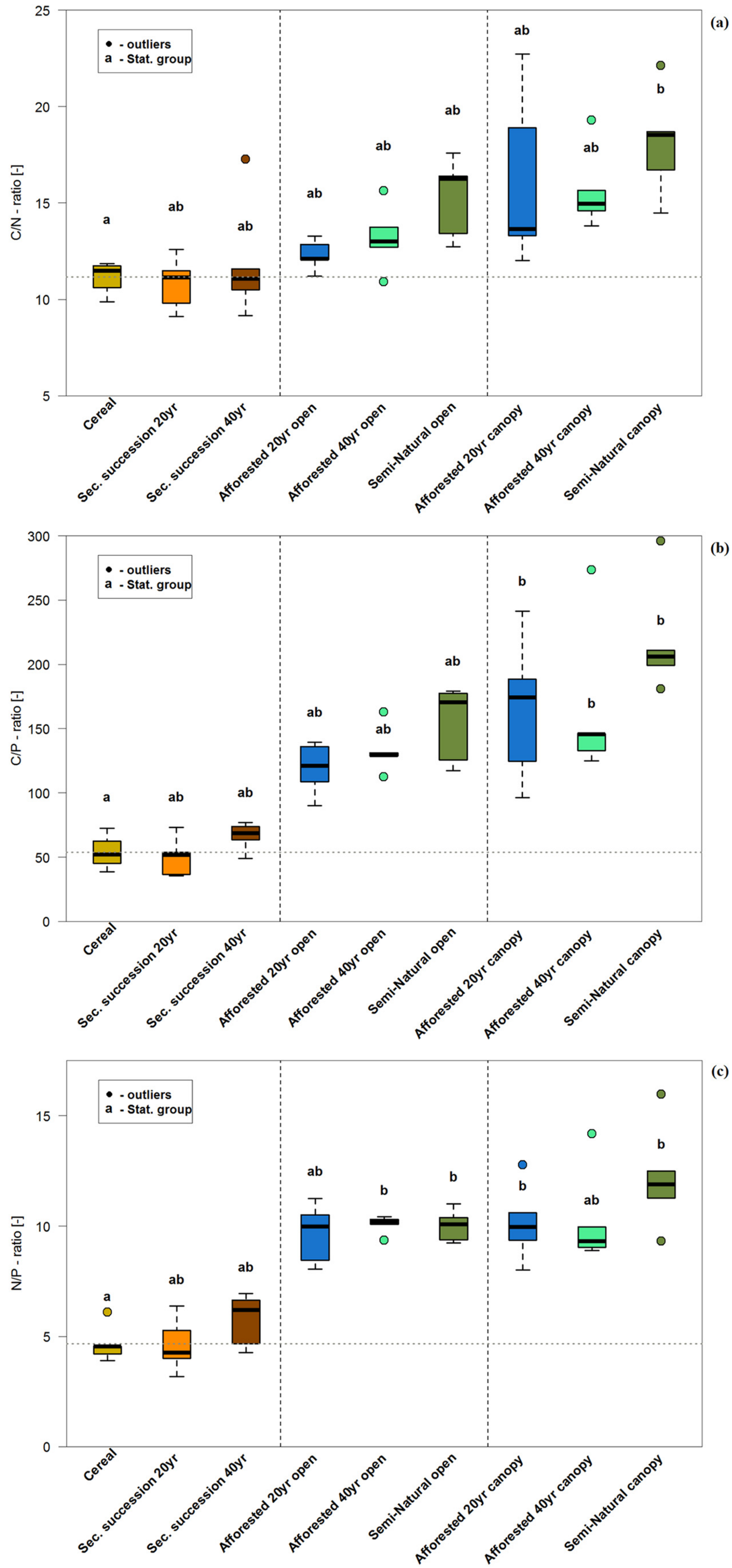

Fig. 7. Box-and-whisker diagrams showing the median (black line), 25th, 75th (resp. upper/lower part box) and min./max. Value (whiskers) for C:N ratio (a), C:P ratio (b) and N:P ratio (c). The horizontal grey line represents the mean value found in the "Cereal field" plots.

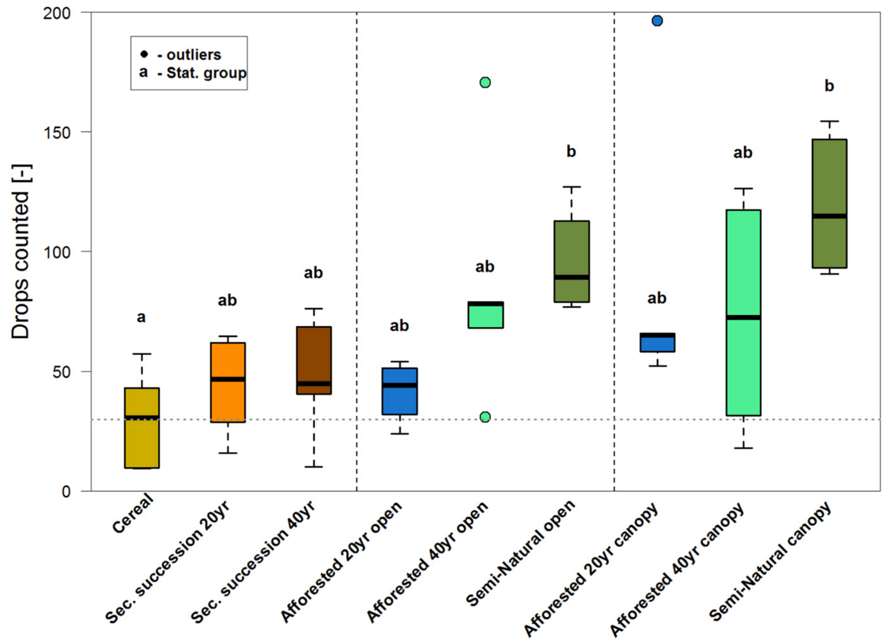

Fig. 8. Aggregate stability of 4–4.8 mm aggregates, measured by the water drop impact method, is displayed in the box-and-whisker diagrams showing the median (black line), 25th, 75th (resp. upper/lower part box) and min./max. Value (whiskers). The horizontal grey line represents the mean value found in the "Cereal field" plots.

with an enhanced aggregate stability. They also showed that the bacterial community gradually changed from bacteria dominated agricultural soils to a more diverse microbial community in natural sites. For instance, Goberna et al. (2007) demonstrated that after 20 years of afforestation the microbial community was smaller and less active under similar conditions as the current sites. This conjunct with the field observation that only in some of the 40-year-old afforested plots, the litter was colonized with fungal hyphae, indicating a lively fungal community. The large spreading of the aggregate stability observed between the 40-year-old afforested canopy plots, might be a result of the differences in recovery stages between the plots.

4.3. Enhancing effect afforestation

In contrast to the secondary succession after land abandonment, afforestation introduces within a decade a tree cover, which provides besides soil protection also a source of litter input that increases over time with the development of the trees. The rate of canopy development/tree performance in this semiarid environment is largely determined by inter-annual changes in water availability (Moreno-Gutiérrez et al. 2012). On the other hand, the vegetation cover and composition changes under secondary succession, which is reflected in a non-linear soil quality change over time (Bonet, 2004; Lesschen et al., 2008; Lozano et al., 2014). This results even in a reduction for many soil quality parameters after 15–25 years under semiarid climate conditions (Cammeraat and Imseon, 1998; Gabarrón-Galeote et al., 2015; Lozano et al., 2014).

Increase in SOM is mostly associated with an increase in soil hydrophobicity, especially under the wax/aromatic oil rich litter of the *Pinus halepensis* trees (Mataix-Solera et al., 2007). Despite increased hydrophobicity of the soil surface, rainwater might infiltrate much quicker via preferential flow paths to deeper hydrophilic soil layers, which enhances the water availability in the resource island (Gabarrón-Galeote et al., 2013; Imeson et al., 1992). Also the difference in bulk density hints to an increased soil porosity, most likely a combination of biological activity, increased SOM content and the reworking of the soil by the afforestation practice (Cortina et al., 2011; Van Hall et al., 2017). Water repellency is also an important factor for aggregate stability in calcareous soils (Chrenková et al., 2014), which might partly explain the observed difference in aggregate stability between afforestation and secondary succession that was observed (Fig. 7).

This study focused only on the top 10 cm of the mineral soil, which is most affected by land use conversion (Fernández-Ondoño et al., 2010; Nadal-Romero et al., 2016). Furthermore, in the study area a calcrete is present at a depth of ~25 cm, due to which deeper sampling was not possible. Additional samples, taken between 10 and 20 cm, showed similar but damped trends as found in the first 10 cm (see supplementary material). The sampling between the canopy and open area indicated also an important difference that is mostly not taken into account. Despite that Fernández-Ondoño et al. (2010) showed also a difference between the canopy and open area and Ruiz-Navarro et al. (2009) indicated differences between microsites, this aspect is mostly not considered in soil interaction with land use change impact studies. This hampers the understanding if or when the natural resource islands are formed after land use change. Following the observed trends and taking into account that the trees are still in a growing stage after 40 years, one can hypothesize that a new stable state with a higher soil quality value compared to the (semi-)natural vegetation could be reached after some more time. This can also be the result of the fact that the afforested trees are planted in the soil under the calcrete, giving them the possibility to obtain additional nutrients and water from deeper soil layers.

Despite the relative clear results presented in this paper, for every case a site specific solution should be obtained (Keesstra et al., 2018). For instance, the usefulness of afforesting current shrublands can be questioned, as it will most likely lead to a reduction in species richness (Bremer and Farley, 2010). Restoration of degraded lands should at least aim at reversing the effects of degradation by improving soil conditions, increasing plant cover, and introducing key-stone woody species (Cortina et al., 2011). Nevertheless, the presented study showed that a monoculture can still improve soil quality. One should consider however that the local ecosystem becomes more vulnerable to diseases, plagues and wildfires when monoculture plantations are used (Maestre and Cortina, 2004). Also the climatic effect on secondary succession has to be taken into account, as under slightly wetter climate conditions (800 mm annual rainfall), secondary succession turned out to be effective as afforestation for soil restoration in the longer term (Nadal-Romero et al., 2016). Already local climate differences by for instance slope aspect could also be induce differences in secondary succession on a relative small scale (Van Hall et al., 2017). The question if the financial investment in such an afforestation project is feasible, should be answered for every case individually. Above all the goal of the implemented measures, e.g. protection of the soil or improving the local environment, should have an important impact on the decision making.

5. Conclusion

This study provided insight in the soil development by secondary succession or afforestation on abandoned agricultural fields under a semiarid climate. The most important findings were:

- Secondary succession on abandoned agricultural fields showed minor non-linear improvement over 40 years.
- After 40 years, afforestation resulted in a soil status comparable to the semi-natural vegetation and forms the typical resource islands ecosystem.
- To reach a similar recovery of soil quality on abandoned field, a substantial longer time is needed, meaning that the soil remain longer prone to degradation as vegetation cover lacks and soil stability is still degraded.

The main changes observed in the soil parameters were driven by an increase of SOM. Soil aggregate stability related significantly to SOM content, but despite a similar SOM content between afforestation and semi-natural vegetation, the aggregate stability was still substantial lower in afforested sites. This indicated that there are more influencing factors, like a changing soil microbial community and/or difference in litter quality input, for aggregate stability.

Overall it seems that the site preparation, the creation of furrows in the present calcrete for planting the trees, played an important role in the success of the afforestation. It highlights the importance of site specific solutions for restoring or greening dryland ecosystems.

Declarations of interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.10.235.

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