Irrigation agriculture affects organic matter decomposition in semi-arid terrestrial and aquatic ecosystems

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Abstract

Many dryland areas are being converted into intensively managed irrigation crops, what can disrupt the hydrological regime, degrade soil and water quality, enhance siltation, erosion and bank instability, and affect biological communities. Still, the impacts of irrigation schemes on the functioning of terrestrial and aquatic ecosystems are poorly understood. Here we assess the effects of irrigation agriculture on breakdown of coarse organic matter in soil and water. We measured breakdown rates of alder and holm oak leaves, and of poplar sticks in terrestrial and aquatic sites following a gradient of increasing irrigation agriculture in a semi–arid Mediterranean basin transformed into irrigation agriculture in 50% of its surface. Spatial patterns of stick breakdown paralleled those of leaf breakdown. In soil, stick breakdown rates were extremely low in non-irrigated sites (0.0001–0.0003 day^{-1}), and increased with the intensity of agriculture (0.0018–0.0044 day^{-1}). In water, stick breakdown rates ranged from 0.0005 to 0.001 day^{-1}, and increased with the area of the basin subject to irrigation agriculture. Results showed that irrigation agriculture affects functioning of both terrestrial and aquatic ecosystems, accelerating decomposition of organic matter, especially in soil. These changes can have important consequences for global carbon budgets.

Keywords: irrigation agriculture, ecosystem functioning, breakdown, stream, soil

1. Introduction

Human activities are transforming dramatically the world’s landscape [1], what probably represents the most important component of global environmental change [2]. Extensive natural areas are being converted for human use, and management practices are intensifying in already human-dominated lands [3]. The area of cultivated land increased globally 466% from 1700 to 1980 [4], to such an extent that croplands and pastures have become one of the largest biomes on the planet [5–6]. More recently, this expansion has slowed down, but, even so, yields keep increasing considerably [7]. This increase is a consequence of the so-called "Green Revolution", which promoted the expansion of high-yielding crops that depend on the use of potentially hazardous materials such as synthetic fertilizers and pesticides, and on the implementation of irrigation and mechanization. As a result, the irrigated surface has doubled during the last 50 years [8–9] and the use of fertilizers increased seven-fold [10]. Moreover, future projections related with global change claim for further expansion of irrigated lands

[1,11] in order to compensate the rising temperatures [12], the altered seasonality [13] and the enhanced torrentiality [14]. Highly populated areas with a shortage of water availability, like the Mediterranean region, will be most dependent on the increase of irrigation to ensure their agricultural supply, and this will likely imply transformation of non–irrigated croplands as well as of non–agricultural lands.

Modern agricultural techniques result in increased productivity, but often at a high environmental cost leading to unacceptable environmental alterations [3,15]. Irrigation disrupts the hydrological regime [16–17], whereas fertilizers and pesticides pollute soils and nearby aquatic ecosystems [18–20]. These impacts can lead to soil acidification [21], salinization [22], eutrophication and hypoxia [23], water quality issues [24], as well as being a critical source of greenhouse gases [1,3,25]. Moreover, agricultural streams are often associated with high siltation, erosion and bank instability [22,26], which reduce habitat quality [27] and affect the composition and structure of biological communities [28–29]. These environmental impacts could affect the functioning of aquatic and terrestrial ecosystems, eroding their resilience and undermining many ecosystem services [30–31]. Therefore, for a sustainable future it is crucial to understand how ecosystem functioning is altered by irrigation agriculture.

Ecosystem functioning includes a wide variety of processes that change at different spatial and temporal scales and respond to environmental changes specifically [32]. Decomposition, usually measured in terms of leaf litter breakdown, is one of the most broadly used functional variables to assess the impacts of environmental changes on the functioning of both terrestrial [33–34] and aquatic [35–36] ecosystems. Standard wooden sticks are a cost–effective alternative to leaf bags to assess the functional impairment of ecosystems [37–39]. Breakdown of organic matter integrates physical abrasion, microbial colonisation, and invertebrate fragmentation [40] and is a key process in the cycling and storage of carbon and nutrients in terrestrial and aquatic ecosystems [41–42]. In addition, it is sensitive to many anthropogenic stressors including flow regulation [43], pollution [44–45], eutrophication [46], changes in riparian vegetation [47–48], or loss of biodiversity [49–50]. However, because each stressor can push breakdown in a different direction and interactions between stressors are common in agro-ecosystems exposed to multiple stressors simultaneously, it is difficult to forecast the overall effect on decomposition [38].

This study assesses the impacts of intensive irrigation agriculture on the functioning of terrestrial and aquatic ecosystems in a semi-arid landscape. The main goal is to compare the breakdown of standard wooden sticks in terrestrial and aquatic sites exposed to a gradient of irrigation intensity. Because this tool has only been validated recently, we also compared the response of wooden sticks with that of classical leaf bags. We hypothesized that: a) the breakdown of wooden sticks will follow the same patterns than leaf bags; b) irrigation will promote breakdown in soils, as water availability is strongly limiting in semi-arid regions; and c) irrigation will also result in higher breakdown in aquatic ecosystems because of higher nutrient contents in the returning water from agricultural fields to streams.

2. Materials and Methods

2.1 Study area

Breakdown experiments were performed in the the Lerma Creek basin, in the Ebro Depression (Spain). It is located south from the pre-Pyrenees, in the semi-arid Bardenas sector of the Mediterranean region. The climate is continental with an annual precipitation of 468 mm, occurring mostly in spring and fall, whereas severe droughts occur in summer. The annual mean temperature is 14 °C, and the monthly mean varies between 5 °C in January/February and 23 °C in July/August (data from the nearby town of Ejea de los Caballeros).

The Lerma Creek drains a basin of 752 ha that has been recently transformed to irrigation agriculture in almost 50% of its surface. Sprinkler (86%) and drip irrigation (14%) are used to grow mainly maize, winter cereals and tomato. Irrigation in the area enabled double cropping, thanks to an increase in the amount of water, fertilizers and pesticides applied annually per hectare. The common agricultural practices consist of sowing fertilization with NPK compounds, followed by urea (46% N) and/or multiple applications of liquid fertilizers (16% urea, 8% ammonia and 8% nitrate). The predominant active principles of the pesticides used are metolachlor, terbuthylazine and chlorpyrifos, and also included athrazine in the recent past [51].

Irrigation had deep effects on the hydrological regime. The median of daily flow at the Lerma basin increased significantly, the intermittent main creek became perennial and seasonality shifted from a rain-driven to an irrigation-driven pattern [52]. This increased the export of salt from the basin, reduced water salinity due to dilution, and increased the concentration and export of nitrate [53]. Abrahao et al. [51] found slightly elevated values of endrin in the soil, pp'-DDT in water and Ni and Zn in the sediments. However, overall, no serious contamination was detected related to the substances they analyzed (44 pesticides and metabolites, 11 organochlorinated compounds, 17 polycyclic aromatic hydrocarbons, 13 polychlorinated biphenyls and several metals and metalloids).

We selected terrestrial and aquatic sites following a gradient of increasing irrigation intensity (Fig. 1). Terrestrial sites ranged from natural shrubby vegetation above the irrigated area (Shrubland) to irrigated crops (Cropland), passing through non–irrigated pine plantations (Pine Plant), with some differences in soil characteristics (Table 1). Non–irrigated sites were set in the valleys of the Lerma gully, predominated by emerging tertiary materials with a small effective depth limited by limestone and tabular gypsum, and slow drainage. On the contrary, croplands were located in the quaternary glacis consisting of deeper layers of gravels with a sandy loam matrix and layers of tertiary materials [52]. Aquatic sites included the main irrigation canal, and 3 stream reaches with increasing area of irrigation agriculture in their drainage basins, and considerable differences in conductivity and nutrient concentration (Table 2).

2.2 Breakdown experiment

Breakdown experiments were carried out with tongue depressors (15 × 1.8 × 0.2 cm) made of untreated Canadian poplar wood (*Populus nigra* × *canadiensis*, Moench 1785). Wooden sticks were numbered, oven–dried (70 ºC, 72 h), weighed and assembled in strings of 5 with fishing line. Sticks were buried (5–10 cm) in terrestrial sites, and tied to metal bars or roots in water. In order to check whether the response of wooden sticks was consistent to that of traditional leaf bags, we also incubated fine (100 μm) and coarse (5 mm) mesh bags with leaves of holm oak (*Quercus rotundifolia* Lam.) in two of the sampling points in soil (Gully and Cropland2), and fine (100 μm) and coarse (5 mm) mesh bags with leaves of alder (*Alnus glutinosa* (L.) Gaertner) in the four sampling points in water. Fine mesh bags exclude invertebrates, enabling to discern the contribution of microbial and invertebrate communities to the overall decomposition. Freshly fallen holm oak and alder leaves were collected in autumn 2010, air-dried at room temperature (21 °C), enclosed in labelled bags (3 ± 0.05 g in holm oak bags and in fine alder bags; 5 ± 0.05 g in coarse alder bags) and buried and tied like wooden sticks.

All materials were retrieved after 43, 75, 219 and 371 days (5 replicates per site and material), except for alder bags which were collected after 14, 43 and 75 days due to their faster decomposition. The rainfall during the incubation period was 260 mm, lower than the long-term average but within the natural interannual variability. Upon removal, sticks and bags were stored in individual zip-lock bags and carried to the laboratory on ice. Samples were rinsed with tap water to remove invertebrates and mineral particles. The material was oven-dried (70 °C, 72 h) and ashed (500 °C, 5 h) to determine the ash free dry mass (AFDM). Initial dry mass of sticks and alder bags incubated in water was corrected for leaching to exclude the effect of this site-independent chemical process, and the remaining AFDM was fitted to the negative exponential model to calculate breakdown rates [54].

2.3 Data treatment

The response of different materials was compared by two-way ANCOVAs (k rate as dependent variable, site and material as fixed factor, and time as covariable) and by computing ratios of breakdown rates between different sites for each material [35].

Differences in breakdown rates of wooden sticks were analysed by means of one-way ANCOVAs (k rate as dependent variable, site as fixed factor, and time as covariable) and post-hoc Bonferroni tests. Pearson's correlation coefficients were calculated between breakdown rates and the rest of the variables, and a Principal Component Analysis (PCA) was also performed to identify the main factors explaining the differences among breakdown rates in soil.

3. Results

3.1 Wooden sticks versus leaves

There were large differences among materials in breakdown rates in both terrestrial and aquatic ecosystems (soil: $F_{1,132} = 132.6$, $p < 0.0001$; water: $F_{2,206} = 115.1$, $p < 0.0001$; Fig. 2). Leaf litter in coarse mesh bags broke down the fastest and wooden sticks the slowest, except for Cropland2, where holm oak in fine mesh bags broke down slower than sticks. Differences among sites were also statistically significant (soil: $F_{2,132} = 27.03.6$, $p < 0.0001$; water: $F_{3,206} = 4.35$, $p = 0.005$), but spatial variations depended on the material. The increase in breakdown rate was much higher for coarse mesh than for fine mesh bags, especially in soil, and the interaction site x material was significant (soil: $F_{2,132} = 21.7$, $p < 0.0001$; water: $F_{6,206} = 2.27$, $p = 0.038$). Moreover, ratios of breakdown rates computed with different materials were highly variable and showed no consistent pattern (Table 3). Nevertheless, coarse mesh bags and sticks displayed consistent patterns and the site x material interaction became non-significant when fine mesh bags were removed from the analysis (soil: $F_{1,86} = 0.595$, $p = 0.442$; water: $F_{3,134} = 2.09$, $p = 0.105$).

3.2 Impacts of irrigation agriculture

In the terrestrial environment irrigation agriculture accelerated decomposition. Stick breakdown rates were extremely low in non–irrigated sites (0.0001–0.0003 day^{-1}), and increased significantly with the intensity of irrigation (0.0018–0.0044 day^{-1}; Fig. 3). According to the post–hoc Bonferroni test, the sampling points could be grouped in three groups regarding breakdown rates: they were slowest in non–irrigated sites, 5–16 times faster in Cropland3, and fastest in Cropland1 and Cropland2.

The regression between water availability and breakdown rates was only marginally significant ($p = 0.054$), being content of $CaCO_3$, sand and silt the only variables significantly correlated with stick breakdown rates in soil, all of them strongly inter–correlated ($p < 0.05$). However, breakdown rates were strongly correlated with the first of the two main components extracted for the PCA analysis, which together accounted for 81.8% of the variance (Fig. 4). The first axis was significantly correlated with water availability, carbon content, granulometry and number of bacteria (both alive and harmed or dead) in soils. The second axis was correlated with N content and pH. Differences between the non–irrigated sites and the three croplands were mainly influenced by the main component, whereas the second axis explained the differences between the non–irrigated sites.

In the aquatic environment stick breakdown rates ranged from 0.0005 to 0.001 day^{-1}, and increased significantly downstream, with the area of the basin subject to irrigation agriculture (one–way ANCOVA: $F_{3,62} = 18.8$, $p < 0.0001$; Fig. 5). The only variable significantly correlated with stick breakdown rates in water was PO_4^{-3} ($R^2 = 0.9$, $p = 0.049$). The regression between NO_3^- and the area under irrigation was statistically significant ($R^2 = 0.98$, $p = 0.007$), but neither NO_3^- nor the area under irrigation were strongly correlated with breakdown rates ($p > 0.05$). Besides, spatial differences in water were not as abrupt as in soil, and according to the post-hoc Bonferroni test the sampling points could be grouped in two highly overlapping groups (Fig. 5). Maximum differences in breakdown rate were also smaller in water (5X) than in soil (44X).

4. Discussion

4.1 Wooden sticks versus leaves

The response of wooden sticks to environmental stressors caused by irrigation agriculture was consistent to that of coarse mesh bags in both terrestrial and aquatic ecosystems, thus suggesting their breakdown integrates the effects of microbial activity and consumption by invertebrates. Sticks have been used in streams as indicators of functional impairment [37–38], as they are a cheaper and less time consuming alternative to leaf bags [39]. Our results suggest their use can be expanded to assess soil functioning. Their slow decomposition would make them especially suitable for routine use with one year incubations, less so for shorter time frames. A related question is how to define thresholds for functional impairment based on breakdown rates. Gessner and Chauvet [35] proposed to use the ratio of breakdown rates between test and reference sites, and gave specific values to indicate moderate and strong impairment in streams. Nevertheless, in the present experiment these ratios resulted extremely variable depending on the material used, a result paralleling those reported by Arroita et al. [39]

in large streams. Therefore, although wooden sticks offer a cheap, quick and reliable method to measure breakdown in different ecosystem types, clearly more research is needed to adequately define the metrics and the thresholds for functional impairment.

4.2 Impacts of irrigation agriculture

Agricultural practices have deep effects on the characteristics and functioning of soil and nearby water ecosystems [55]. As hypothesized, intensive irrigation agriculture affected the functioning of terrestrial and aquatic ecosystems, accelerating decomposition rates of organic matter irrespective of the type of material. Besides, the fact that irrigation accelerated more the breakdown of leaf litter in coarse than in fine mesh bags indicates that it affected both microbial and invertebrate activities. Our limited dataset precludes attributing enhanced breakdown rates to specific environmental variables, but increased water and nutrient availability seems to be the main factor promoting biological activity in this semi-arid area.

Regarding the terrestrial environment, our results confirm the well-known effect of agriculture on enhancing the cycling of materials in soils. Organic matter breakdown depends on soil moisture, temperature and nutrient contents [56–57], and tends to be promoted in agricultural soils, up to the point of reducing their contents on organic matter [58–64]. In agricultural areas, primary production greatly increases as a consequence of irrigation, thus amounting to a large sequestration of CO_2 in biomass. Nevertheless, the effects of agriculture on the global carbon budget depend largely on the fate of agricultural products. There are no data on agricultural primary production in the study area, but it clearly increased when irrigation was implemented, as the number of crops per year doubled, and low–biomass crops such as wheat were substituted by high biomass ones such as corn. Nevertheless, for most of the irrigated crops such as corn or tomato, only grain or fruits are harvested and most of the biomass is left on the ground. Therefore, the fact that we found lower contents of organic matter in the irrigated soils indicates that breakdown also increases greatly, to the extent of matching primary production.

The most important factor accelerating breakdown of organic matter seems to be water availability [65], especially in semi–arid regions, as moisture promotes microbial activity, thus enhancing decomposition [66–67]. In the Lerma gully, the implementation of irrigation led to a progressive increase in evapotranspiration [52], which has been shown to result in accelerated breakdown [68]. Furthermore, artificial remoistening of dried soil by irrigation disrupts soil structures, increasing substrate availability for bacteria, further enhancing microbial activity [69]. Concerning temperature, irrigation agriculture has been shown to contribute to the reduction of the diurnal temperature range [70], what could slow down decomposition [71]. However, our results suggest that factors enhancing breakdown (moisture) were much stronger than factors decelerating it (reduced temperature oscillations).

Other potential factors behind enhanced breakdown are soil texture, ploughing, and fertilization. Soil texture affects decomposition [69] through their effects on vertical migration of organisms and aeration [72], both of them decisive factors in breakdown [73]. The fact that breakdown rate was located close to the firs axis in our PCA, and not close to the nutrient contents, suggests soil texture to be a determinant factor of the observed differences. Nevertheless, a potential confounding factor is the fact that non–

irrigated sites in the Lerma basin are mainly located on tertiary clays, whereas most croplands are located in more sandy quaternary glacis. Their composition makes quaternary glacis more suitable for irrigation, explains part of the differences in soil texture, and might play a role in breakdown rates. A point of concern is the higher percentage of dead bacterial cells in croplands in the present experiment, which might reflect soil toxicity, probably as a consequence of pesticides and heavy metals, which appear in fairly high concentrations in the Lerma basin [51]. The combination of heavy metals and organic pollutants causes synergistic cytotoxic effects on microorganisms [74].

Although we lack any data previous to the implementation of irrigation agriculture in the Lerma basin, the observed spatial patterns suggest that it enhanced the breakdown of organic matter. On one hand, irrigation converted the Lerma Creek from intermittent to perennial [52], and it is known that stream intermittency results in slow breakdown [75–77]. On the other hand, the spatial gradient of intensification produced an acceleration of breakdown rates. Nutrient concentrations in water enhance breakdown rates [78–80] up to a point beyond which they can fall again [36]. Additionally, agricultural practices can have multiple effects on river ecosystems, from altered hydrology to siltation or pesticide toxicity, all of which can have important consequences for ecosystem functioning [81–82]. Therefore, it is not rare to find large variability on breakdown rates in rivers subject to multiple stressors [38]. Nevertheless, our results show that in the Lerma Creek the spatial differences can be explained by nutrient concentration, thus suggesting other factors to play a minor role.

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Table

Table 1. Irrigation water applied, water availability, content of soil organic carbon (SOC), soil inorganic carbon (SIC), total nitrogen (N_{TOT}), $CaCO_3$, sand, silt and clay, pH and number of bacteria alive (B_A) and bacteria harmed or dead (B_{HD}) in the sampling points in soil.

SITE	Irrigation (mm)	Wat. Avail. (mm)	SOC (%)	SIC (%)	N_{TOT} (%)	$CaCO_3$ (%)	Sand (%)	Silt (%)	Clay (%)	pH	B_A ($cell \cdot g^{-1}$)	B_{HD} ($cell \cdot g^{-1}$)	B_{HD} (%)
SHRUBLAND	0	7.15	4.39	2.32	0.167	34.6	46.8	33.1	20.1	8.41	7.88E+06	9.55E+04	1.2
PINE	0	7.15	4.81	2.49	0.285	34.1	57.8	31.2	10.9	5.74	3.05E+07	1.14E+06	3.6
GULLY	0	10.8	4.10	2.14	0.060	34.3	47.9	38.0	14.1	7.98	9.01E+06	1.53E+05	1.67
CROPLAND1	726	17.4	3.67	1.55	0.114	29.7	65.2	22.9	11.9	7.98	2.47E+07	8.63E+06	25.9
CROPLAND2	683	14.3	4.01	1.64	0.101	29.0	73.5	17.4	9.1	8.23	1.25E+07	2.40E+06	16.1
CROPLAND3	706	12.0	3.31	1.31	0.141	28.3	66.4	22.8	10.9	8.28	4.57E+07	9.86E+06	17.8

Table 2. Characteristics of study sites in water (mean ± SE).

SITE	Irrigated area		Cond.	pH	O_2	NO_3^-	PO_4^{-3}
	ha	%	($\mu S \cdot cm^{-1}$)		($mg \cdot L^{-1}$)	($\mu gN \cdot L^{-1}$)	($\mu gP \cdot L^{-1}$)
CANAL	0	0	246 ± 10	8.50 ± 0.08	9.0 ± 1.89	269 ± 89	2.21 ± 0.8
CROPLAND1	22	87	1906 ± 140	8.45 ± 0.04	7.8 ± 1.87	1689 ± 73	5.38 ± 0.9
GULLY	36	35	295 ± 31	7.40 ± 0.90	10.6 ± 0.79	124 ± 95	8.16 ± 3.2
GAUGING STAT.	320	43	3461 ± 319	8.37 ± 0.03	12.1 ± 0.63	22265 ± 380	3.32 ± 1.5

Table 3. Ratios of breakdown rates between different sites for each material.

	Bag 5 mm	Bag 100 μm	Sticks
Gully:Cropland2	0.20	0.46	0.06
Canal:Cropland1	0.69	1.56	0.42
Canal:Gully	0.92	1.30	0.20
Canal:GaugingStat	0.59	0.94	0.43
Cropland1:Gully	1.34	0.83	0.47
Cropland1:GaugingStat	0.85	0.60	1.02
Gully:GaugingStat	0.64	0.72	2.18

Figure

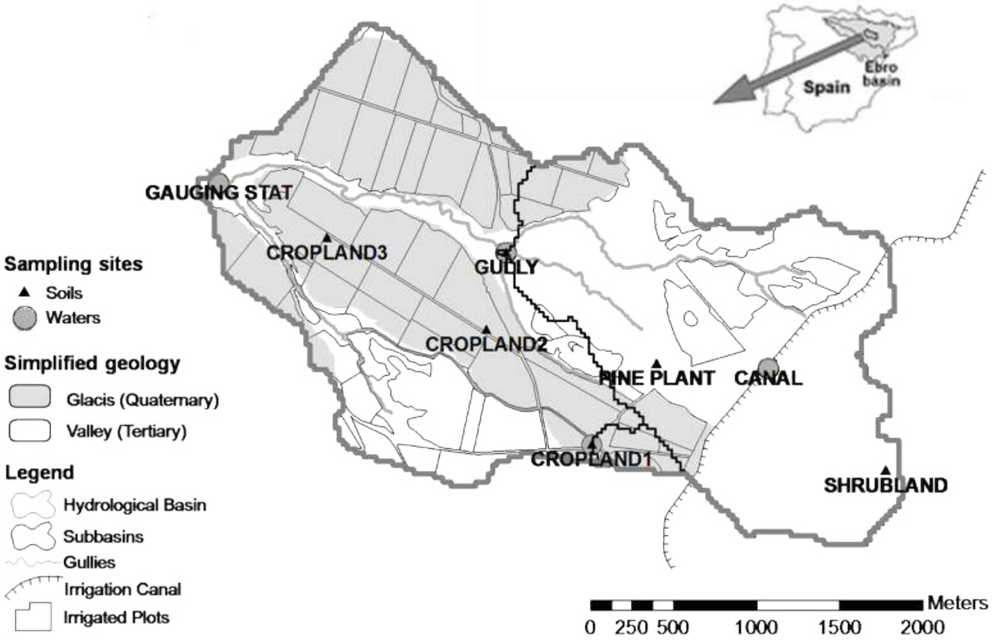

Fig. 1. Physical setting of the Lerma basin and sampling sites.

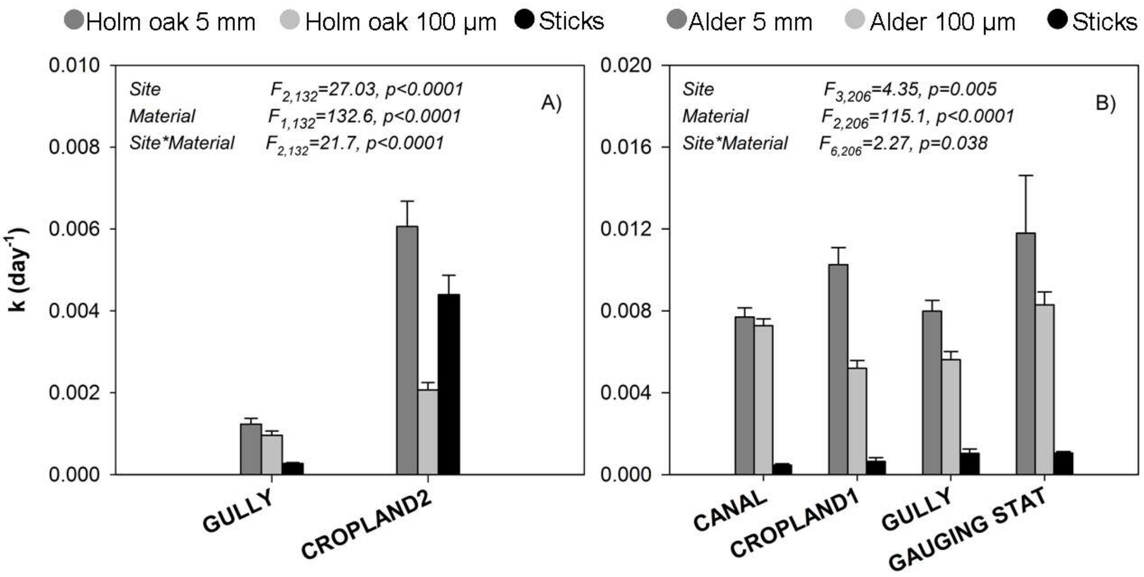

Fig. 2. A) Breakdown rates in soil (day^{-1}) of holm oak in fine and coarse mesh bags, and of poplar sticks. B) Breakdown rates in water (day^{-1}) of alder in fine and coarse mesh bags, and of poplar sticks. Error bars show SE. Results from two-way (site x material) ANCOVA are also shown.

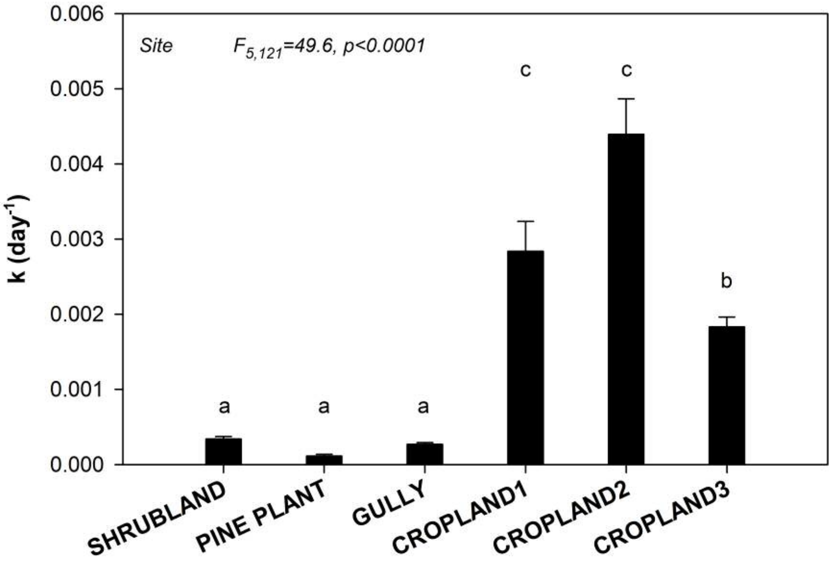

Fig. 3. Breakdown rates (day^{-1}) of wooden sticks in soil. Error bars show SE. Results from post-hoc Bonferroni test after one-way ANCOVA with site as a factor are also shown.

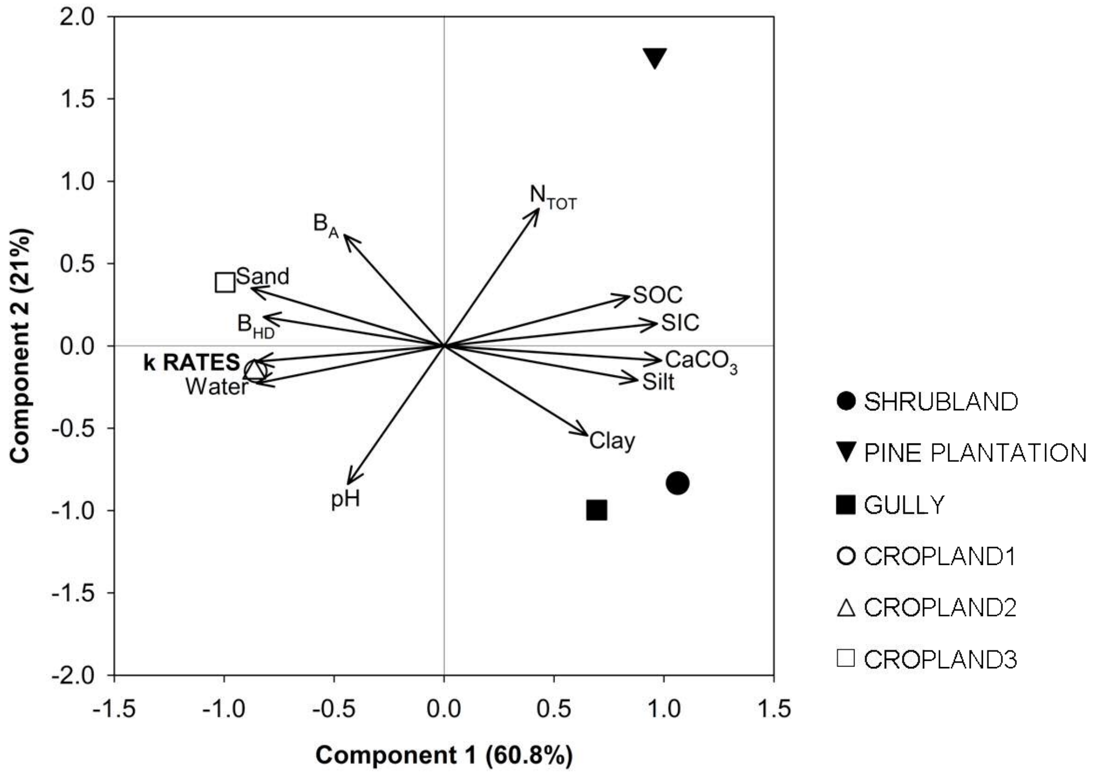

Fig. 4. Principal Component Analysis with breakdown rates, water availability, soil organic carbon (SOC), soil inorganic carbon (SIC), total nitrogen (N_{TOT}), $CaCO_3$, content of sand, silt and clay, pH and number of bacteria alive (B_A) and bacteria harmed or dead (B_{HD}) in each site.

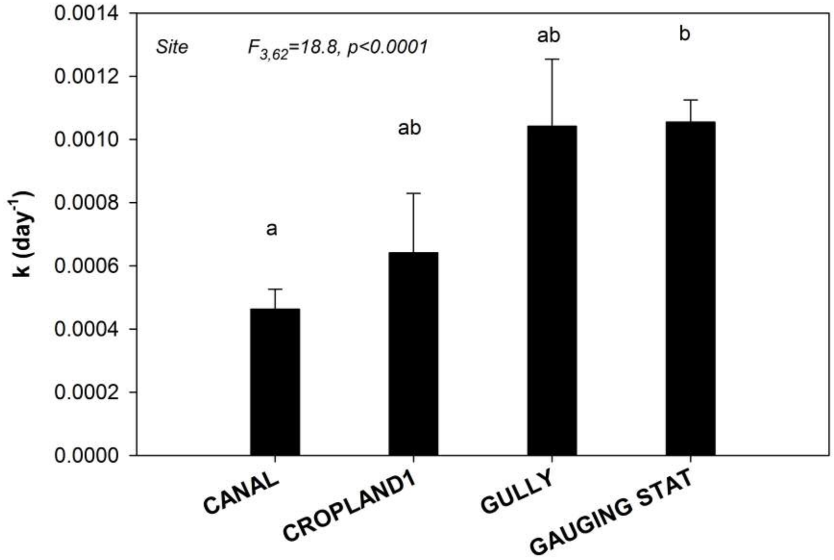

Fig. 5. Breakdown rates (day^{-1}) of wooden sticks in water. Error bars show SE. Results from post-hoc Bonferroni test after one-way ANCOVA with site as a factor are also shown.