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Ecosystem effects of integrating human-made runoff-harvesting systems into natural dryland watersheds

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ABSTRACT

Runoff-harvesting systems (RHSs) design to collect runoff water and nutrients from small rocky watersheds into ponds bounded by soil dikes (termed *limans*) that are used as an afforestation grove. Our study aimed at quantifying the influence of RHSs using two indicators: soil quality (SQ) and aboveground net primary productivity (ANPP) in a small watershed scale. The SQ index was estimated by 13 physical, chemical, and biological soil properties. ANPP was evaluated by a spaceborne-derived vegetation index of total biomass (woody and annual) and field measurements of annuals. The study was conducted in four small RHS watersheds, as well as in a reference watershed without a *liman*, located in the Negev Desert, Israel. Our findings are: (1) there is a significantly higher soil organic matter, total water content, and phosphorus values in all the *limans* than in the other locations (upstream and downstream area); and (2) significantly higher SQ and total ANPP values in the *limans* than in the downstream areas, amplifying the overall watershed fertility and enhance ecosystem services. We conclude that integrating RHS as a fertility island, be adjusted their size and location, can be essential techniques to sustain ecosystem services and maintain the natural ecosystem in the watershed.

1. Introduction

Dryland inhabitants have tried for thousands of years to increase ecosystem services and goods by accumulating scarce resources, mainly water and soil moisture (Brauman et al., 2007; Le Maitre et al., 2007). This was achieved through different runoff-harvesting system (RHS) techniques (Printz and Malik, 2004). All of them basically consist of a relatively large area (source) that contributes runoff water, along with associated resources (e.g., organic matter, nutrients, sediments, and seeds) to a relatively small collection area that gathers and stores the resources (sink). RHSs are situated either along a channel or as contour banks along watershed slopes (Printz and Malik, 2004; Prinz and Malik, 2002). The RHSs create water- and nutrient-enriched patches where planted trees, together with natural understory vegetation (Shachak and Lovett, 1998), create human-made "islands of fertility" within the watershed (Dean et al., 1999; Zaady et al., 2001). These RHSs can be found in different parts of the world and are used to augment and protect crops, improve grazing areas, accelerate tree growth, prevent soil erosion, enrich groundwater, and prevent extreme flooding by regulating the magnitude of runoff events (Ceballos et al., 2002; Evenari et al., 1982; Lavee et al., 1997). Management of productive RHSs in drylands requires an understanding of the complex relationships between water, and nutrient flow on the small watershed scale (Kalavrouziotis et al., 2015; Printz and Malik, 2004; Seka et al., 2016).

RHS were constructed and utilized thousands of years before our present time and were a vital part of the water supply systems of many ancient settlements in drylands (Beckers et al., 2013). These ancient practices based on indigenous knowledge that played an important role in building ancient civilizations and in ensuring greater resilience to climate variability, especially are drier environments (Ashkenazi et al., 2012). Various water harvesting techniques evolved during the Bronze Age or earlier, and some of these remain in use even today (Beckers et al., 2013). Several reviews have addressed the ancient RHS techniques (e.g. Beckers et al., 2013; Evenari et al., 1982; Frasier, 1980; Hudson, 1987; Julius et al., 2013; Oweis et al., 2004; Oweis, 2016). Commonly, RHS techniques are distinguished by the source of water they harvest and are called groundwater harvesting, runoff harvesting, or floodwater harvesting (Cech, 2010). Ancient

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knowledge on RHSs mainly through collection of runoff, storage, and use of rainwater for various purposes, is still relevant, especially in dryland that water resources becoming scarcer under the changing climate (Oweis, 2016).

In the drier areas of the Negev Desert of Israel, with less than 200 mm mean annual rainfall, more than 400 RHSs have been constructed since the early 1960s in the small rocky watersheds of downstream channels alongside roads as a method for creating “human made catchments ” that are known as *limans* and are used for afforested grove (Friend, 2013). Their name originated from the Greek word for pond or pool (Karnieli et al., 1988). The *limans* are ponds bounded by soil dikes located in small watershed. They are used for collecting water and nutrients from the watershed source area, and serve as small sink areas and act as an afforested grove (Printz and Malik, 2004). The *liman* systems may cause the following local effects: (1) they are used as a physical barrier in the form of a soil dike that increases the accumulation rate of runoff, along with its resources, resulting in water, nutrient, sediment, and seed accumulation in the *liman*; (2) the planted trees can modulate the micro-climate regime since the well-developed canopy reduces the sun's radiation beneath it (Potchter et al., 2008); and (3) they are used as area for establishment and immigration of plants and animals that can be inhabited in the resource-enriched patch. A watershed effect may include the modification of the vegetation structure and function in terms of productivity and biodiversity in the entire watershed (upstream and downstream areas) where the *liman* acts as a source of seeds and nutrients (Eldridge et al., 2002). These source-sink relations of runoff water and nutrient to the *limans* are affected by the geo-hydrological processes such as geological and geomorphological characteristics of the specific site locations and runoff regime in the watershed scale (Ashkenazi et al., 2012; Yair, 2001).

The functional and structural changes introduced by the *liman*, on the local and on the watershed scale, can be assessed by two ecosystem indicators, namely the soil quality index (SQI) and aboveground net primary productivity (ANPP) (Paz-Kagan et al., 2014). The first indicator represents an emergent long-term functional property that incorporates the physical, chemical, and biological processes of soil quality (e.g. Andrews et al., 2002; Karlen et al., 2001, 2003). Soil plays an important role in arid ecosystems since it is the only part of the system capable of absorbing and storing water and nutrients during the long hot dry periods (Noy-Meir, 1973). The second indicator, ANPP, is an emergent short-term functional property of ecosystems that integrates many vegetation communities and population processes (Krausmann et al., 2013). We used the ANPP to evaluate the productivity in two different scales, in a watershed and patch scale, as a total ANPP (woody and annuals) and annuals ANPP. We studied the alteration of these two ecosystem indicators between the upstream, the *liman*, and the downstream area. Previous studies compared the conditions inside and outside the RHSs for studding soil conservation (Laryea, 1992), seeds production (Ehlers and Goss, 2016), and plants survival (Lightfoot and Whitford, 1991) along watersheds.

Our aim was to explore the local- and small-watershed-scale effects of *limans* as human-made “islands of fertility” within a natural system in terms of SQI and ANPP (total and annual ANPP) in an arid ecosystem. The specific goals were: (1) to quantify the differences in SQI and ANPP in four watershed between the upstream, the *liman*, and the downstream area, and (2) to study how these two key ecosystem properties modulated and interrelated on a small-watershed scale as a consequence of the introduction of *limans* compared to a natural watershed without a *liman*. The research was carried out by studying thirteen SQ properties, as well as ANPP, in four small arid watersheds containing *limans*, and an additional watershed without a *liman* (a reference for an undisturbed area, without any physical barrier or tree planting). The first hypothesis tested was that in the four small arid watersheds, the *limans* would create a “fertility island” that would affect the redistribution of resources, resulting in increased SQ and ANPP in the overall watershed area. The second hypothesis was that the *liman* would invert the distribution of SQ and ANPP in the watershed scale. In the watershed without *limans*, a higher SQ and ANPP would be found upstream rather than downstream. This would be due to the fact that in small natural watersheds, upstream areas are characterized by higher soil moisture in the channel, due to the high frequency of runoff events resulting from a greater ratio of rock surface to soil volume, than in the downstream areas, where larger sections are covered with alluvium soil (Yair and Kossovsky, 2002). The third hypothesis was that in the downstream areas, degradation in the SQ and ANPP would be expected in all of the small watersheds containing *limans*, as compared to the small watershed without *limans*, due to the physical barrier of the constructed dike that reduces runoff flow to the downstream parts of the channel.

2. Methodology

2.1. Study sites

Five small watersheds located in the central Negev Highlands (30°54 ′ N, 34° 49′ E) were selected to answer the research questions (Fig. 1). Four of these watersheds contain *limans*, and the fifth one is a control watershed without a *liman*. The average watershed area is 52.5 ha, and the average area of the *limans* is 0.4 ha (Table 1). The mean annual rainfall in this area is 95 mm and is limited to the winter season, with a high annual variability (ranging between 20 and 180 mm). During the winter of 2014, the total rainfall depth was 103.9 mm with 21 rainy days. During the winter of 2015, the total rainfall depth was 138.1 mm with 33 rainy days. Geologically, the area is composed of limestone and chalk of the Turonian age. The hillslopes are relatively steep (up to 29°) and subdivided into two distinct sections: (1) the upper parts are mainly barren, with steep limestone rocky outcrops and shallow patches of soil cover; and (2) the lower parts consist of colluvium embedded with unconsolidated rocks (Olsvig-Whittaker et al., 1983; Yair and Danin, 1980). A similar subdivision is also observed along the channels. The upper part of the channel is rocky while the lower part is covered with an alluvial fill (Bruins and Ore, 2008). In general, the *limans* are located in the downstream area of the watershed where there is a relatively high volume of alluvial soil.

The study area is dominated by shrubs and semi-shrubs with an average areal cover of about 25% (Shelef and Groner, 2011). The vegetation in this area is considered to constitute a transition between the Irano-Turanian plant geographical region and the Saharo-Arabian region, with some Mediterranean components. Perennials include the following shrubs and semi-shrubs as dominant species: *Artemisia herba-alba, Gymnocarpos decander, Hammada scoparia, Noaea mucronata, Reamuria negevensis, retama raetama* and *Zygophyllum dumosum* (Shelef and Groner, 2011). The four watersheds containing *limans* include different plantings of introduced tree species: (1) *liman* number 1 was planted with *Eucalyptus occidentalis* and *Pinus halepensis;* (2) *liman* number 2 was planted with *Pistacia atlantica;* and (3) *limans* number 3 and 4 were planted with *Acacia victorae* and *Prosopis alba.* All the *limans* were planted in the 1960s (Table 1).

2.2. Experimental design and sampling

The experiment was performed in the four abovementioned small watersheds in three locations along the watershed: (1)

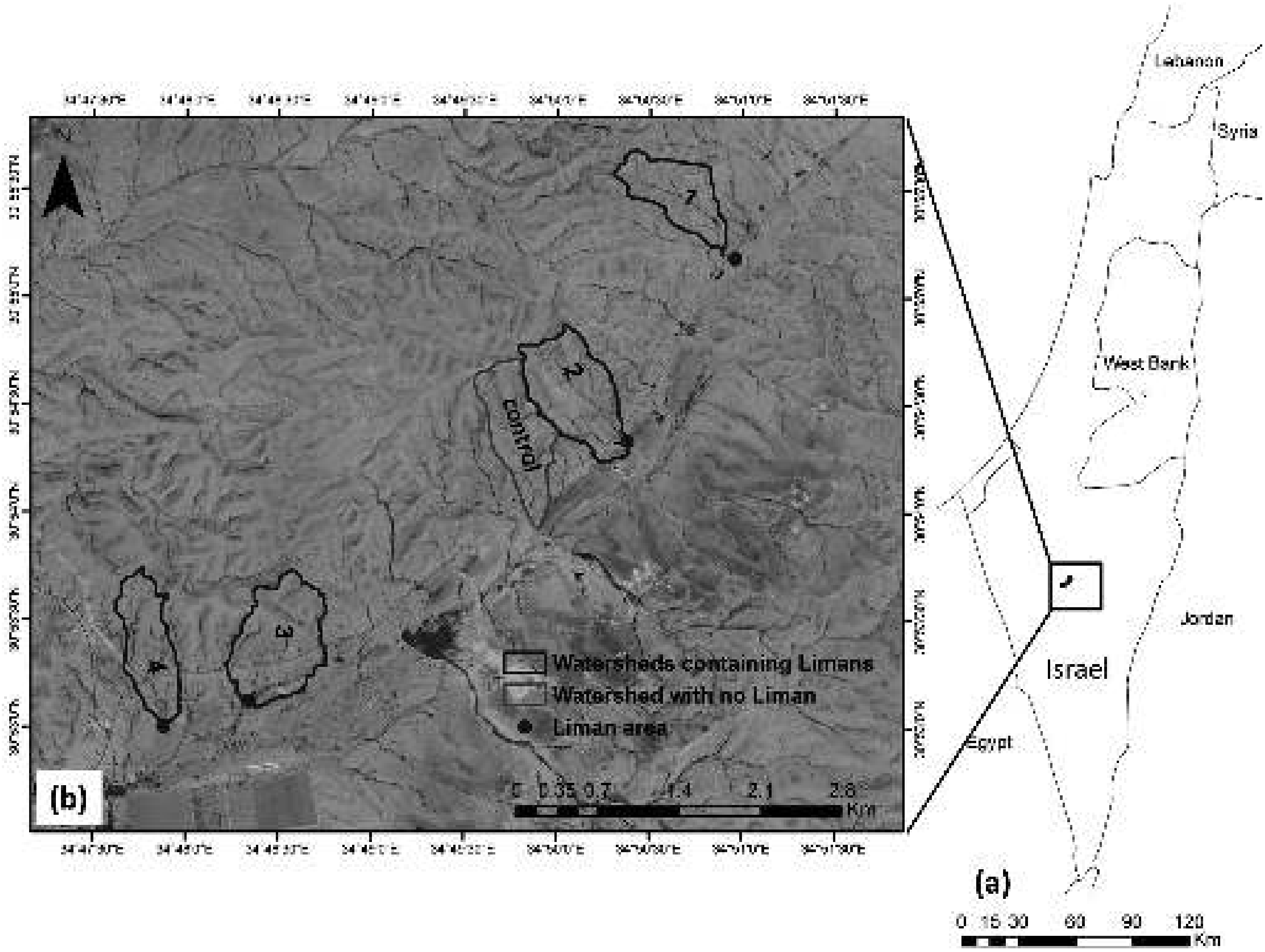

Fig. 1. (a) A semantic map of Israel with the location of the study area; and (b) an aerial photograph of the study watersheds.

Table 1
Information on the study watersheds including: watershed area, *liman* area, and dominant planted tree species.

Liman number	Area of the *liman* (ha)	Catchment area (ha)	Dominant tree species
1	0.6	65	*Eucalyptus occidentalis* *Pinus halepensis*
2	0.5	59.5	*Pistacia atlantica*
3	0.3	31	*Acacia victorae* *Prosopis alba*
4	0.3	52	*Acacia victorae* *Prosopis alba*
Control		55	
Average	**0.4**	**52.5**	

upstream areas, which comprise the lower parts of the hillslopes with colluvium soil cover in the channels; (2) downstream areas, which are mostly constituted by alluvial cover; and (3) *liman* areas, which include the RHS constructions located in the downstream areas (Fig. 2). In addition, the control watershed without *limans* was studied, focusing only on the upstream and downstream areas.

The sampling design for the ANPP in each watershed included two scales: (1) a large scale, using remote sensing data for estimating total ANPP that included estimation of the wood and the annual vegetation at the peak of the growing season in the year 2014; and (2) small scale, estimating annual ANPP at the peak of the growing season in the years 2014 and 2015. The sampling design for the annual ANPP in each watershed included eight samples of 1 m^2, randomly selected in each location of the watershed (upstream, *liman,* and downstream). In each sample, three sub-quadrates of 33 cm^2 were sampled. The sampling areas included a total of 24 sub-quadrates with a total number of 72 sub-quadrates in a watershed. In the control watershed, 8 samples with 16 total sub-quadrates were collected with a total number of 48 sub-quadrates for the watershed. The sampling of the soil included 10 replicates in each sampling locations in the watershed ($n = 30$ replicates in a watershed containing a *liman* and $n = 20$ in the

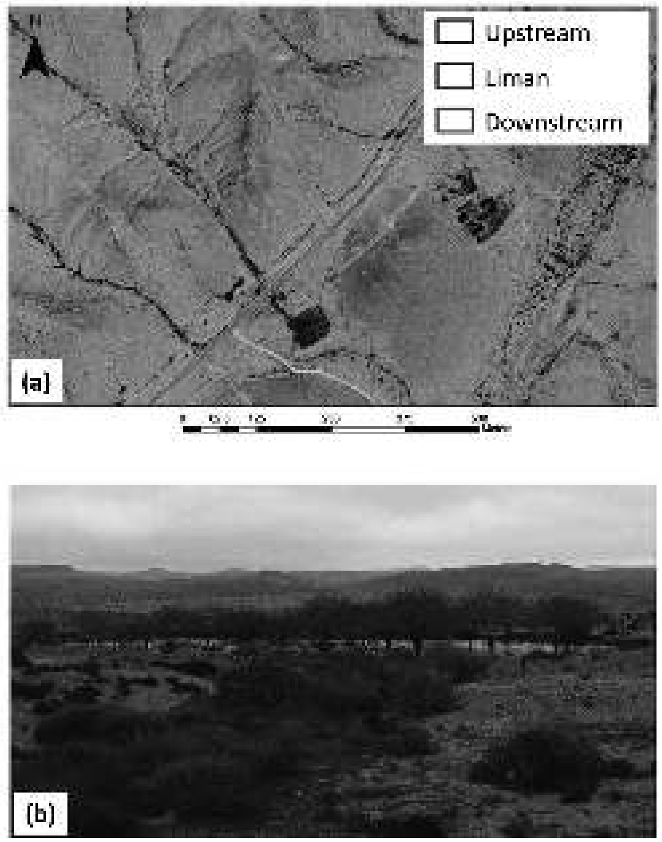

Fig. 2. (a) An aerial photograph of watershed number 2 demonstrating the three sampling areas according to the experimental design: upstream area, *liman* area, and downstream area; (b) photograph of *liman* number 2 with flood water.

watershed without a *liman*) with an overall total of 140 soil samples collected in the year 2015. Detailed information on the sampling design is shown in the supplementary Table S1.

2.3. Soil sampling processing and analysis

The calculation of the SQI included three main stages: (1) selecting the physical, biological, and chemical properties of the SQ; (2) using the transformation function to transform the SQ properties into a unitless scoring function; and (3) using the principal component analysis (PCA) to calculate the weights to develop the SQI (Masto et al., 2008).

2.3.1. Sampling and testing of soil properties

Soil samples were collected in September 2015, at the end of the dry season, at a depth of 0–0.15 m. The sampling was conducted following an experimental design that is described in section 2.2, and was applied to all watersheds containing *limans* and the control watershed. All soil samples were transferred to the laboratory and were stored unopened at room temperature until they were analyzed. The Cornell Soil Health Test (CSHT) protocols were adopted for analyzing thirteen soil properties (Idowu et al., 2009; Moebius-Clune et al., 2016; Schindelbeck et al., 2008). Soil was air dried, passed through a 2 mm sieve, and analyzed for soil physiochemical properties. The physical properties included: (1) soil texture (fractions of clay, silt, and sand) calculated and defined by the relative amounts of sand (0.05–2 mm particle size), silt (0.002–0.05 mm), and clay (less than 0.002 mm) using the hydrometer method (Gee and Bauder, 1979), (2) total water capacity (TWC) measured by drying the soil in 105 C° to, (3) dry aggregation size (AGG) calculated as the ratio between the stable and unstable fractions measured by aggregate stability method, (4) surface hardness (SH) measured with penetrometer, and (5) hydraulic conductivity (HC) measured with mini disk infiltrometer in the field. The biological properties included: (6) soil organic matter (SOM) measured by drying the soil for 2 h at 500 °C (Casida et al., 1964), and potentially active carbon (PAC) was measured by oxidation with potassium permanganate (KMnO4) solution (Weil et al., 2003). The chemical properties included pH that was measured in a saturation paste using a handheld portable probe, electrical conductivity (EC) was measured in the extract from the saturation paste by a handheld portable probe, extractable ammonium (NH_4^+) and extractable nitrate (NO_3^-) were measured by potassium chloride extractions (Norman and Stucki, 1981), extractable phosphorus (P) was measured by the Olsen method (Olsen, 1954), and extractable potassium (K) by flame photometer (Sparks and Rothery, 1996). All laboratory measurements were performed with CSHT standards by Moebius-Clune et al. (2016), however, minor modifications were introduced due to the specific management practices, climatic region, and available tools. Specifically, TWC was measured by the soil moisture, NH_4^+ and NO_3^- were measured by potassium chloride extractions, and HC was measured by a mini-disk infiltrometer in the field. The SH and HC measurements were taken in the field.

2.3.2. Soil quality index

In the current study, the PCA ordination was used twice: (1) as an ordination technique to classify each of the watershed areas according to the different soil properties; and (2) as a model to develop the SQI from the scoring functions of the soil properties. The PCA is probably the most popular multivariate statistical technique for exploratory data analysis and for conducting predictive models (Wold et al., 1987). It uses a rigid rotation to derive orthogonal axes, which maximize the variance in the dataset.

Evaluation of the SQI was carried out using a general approach that involves scoring functions for each of the abovementioned soil properties (Andrews et al., 2004). The scoring functions were defined in a simple nonlinear polynomial framework. Each soil property was transformed through a scoring algorithm into a unitless score (0–1), representing the associated level of function in the system so that the scores could be combined to form a single value (Karlen et al., 1997). The distribution of each of the soil variables was assessed based on a Gaussian distribution function. The interpretation of the scoring function was integrated into an index calculated by the PCA (Efron and Gong, 1983; Masto et al., 2007). The low index values indicate poor soils, while high values indicate healthy soils (Gugino et al., 2009). The soil property values were recorded by the different algorithms (scoring functions, *Si*) to transform each property into unitless scores, using the following equations (Masto et al., 2007, 2008; Svoray et al., 2015):

$$Si_{mib} = \left(1 + e^{-(b(x-a))}\right)^{-1} \quad (1)$$

$$Si_{lib} = \left(1 + e^{(b(x-a))}\right)^{-1} \quad (2)$$

$$Si_{op} = 1 \times e^{\left(-\frac{(x-a)^2}{b}\right)} \quad (3)$$

where x is the normally distributed soil property value, a is the baseline value of the soil property where the score equals 0.5 (inflection point) or the population mean, and b is the slope tangent of the baseline curve or $2\sigma^{-2}$ of the population. The general shape of each function is characterized by the nature of the soil property with respect to SQ, which can be either (1) more is better (*mib*): an upper asymptotic sigmoid curve (negative slope) that characterizes AGG, TWC, SOM, NH_4^+, NO_3^-, K, P, and PAC; (2) less is better (*lib*): a lower asymptote (positive slope) that characterizes SH; or (3) optimum function (*op*): a Gaussian function that characterizes pH, EC and HC. The specific shape and the values were determined according to prior knowledge as presented in the literature and by experts (e.g. Masto et al., 2008; Masto et al., 2007). All of the soil measurement scores were integrated from the previous stage into a single additive index value termed an SQI:

$$SQI = \sum_{i=1}^{n} PWi \times Si \tag{4}$$

where *PWi* is the PCA weighting factor. The SQI value is considered an overall assessment of SQ, reflecting management practice effects on soil function. The PCA finds combinations of variables that describe major trends in the data. Standardized PCAs for each watershed and an additional overall PCA model were performed using the MATLAB program. The equation was normalized to obtain a maximum SQI with a score of one. Principal components (PCs) with eigenvalues higher than one that explained at least 5% of the variations in the data were examined.

2.4. Aboveground net primary productivity

To estimate the total ANPP, a remote sensing image from a RapidEye spaceborne sensor was used with a 7-m pixel ground resolution and five multispectral bands, including red, green, blue, red-edge, and near infrared (NIR). The image was acquired on May 1, 2014, representing the peak of the growing season. The preprocessing of the image included radiometric, atmospheric, topographic, and geometric corrections. The geometric correction was conducted with respect to orthophoto images with a spatial resolution of 0.5 m. For the topographic correction, a digital elevation model with a spatial resolution of 2 m was used. In the present study, the ANPP was evaluated by calculating the commonly used Normalized Difference Vegetation Index (NDVI) (Tucker, 1979). This is a spectral index based on the relations between maximal reflectance in the NIR region, due to leaf internal structure, and minimal reflectance in the red spectral region, due to chlorophyll absorption:

$$NDVI = \frac{\rho NIR - \rho RED}{\rho NIR + \rho RED} \tag{5}$$

where ρNIR and ρRED are the reflectance values in the NIR and red spectral regions, respectively. This index, which is tuned to sense changes in leaf structure and chlorophyll content, has been used successfully to estimate “greenness,” ANPP, leaf area index, and biomass for a variety of ecosystem types (Carlson and Ripley, 1997). Transects of NDVI values from the head of the watershed to the downstream area were examined for each watershed. Line transects were conducted along the upstream, *liman*, and downstream areas through the channel as a function of NDVI values against the distance from the headwater.

In addition to the estimation of the total ANPP, annual ANPP values were measured by the accumulation of annual maximum plant biomass (Fabricius et al., 2003). Plant biomass was measured by quantifying the peak dry mass of plant per unit area in each of the watersheds. Annual vegetation aboveground biomass samples were collected twice during the peak of the growing season (at the end of April) in the years 2014 and 2015. The sampling was conducted using a stratified random method based on the experimental design. All of the replicates were harvested in 0.33-m^2 sub-quadrates (three repeated measurements per sub-quadrate) so that the total number of samples was 336 sub-quadrates in all watersheds as aboveground biomass per year. The annual aboveground plant biomass was weighted, after 48 h of oven drying (75 °C).

2.5. Statistical analyses

Examination of all variables was performed using analysis of variance (ANOVA). The analyses of the ANPP were done by: (1) a general linear model (GLM) analysis of random effect (nested AVOVA); and (2) a one-way ANOVA for the average sample of the sub-quadrates for each replicate ($n = 8$ quadrates). We tested the homogeneity of variances among groups and found that the residuals were normally distributed before applying the ANOVA. The analyses of the SQI were done by applying a one-way ANOVA for the samples for each replicate in each location along the watershed ($n = 10$). In addition, the separation of means was subjected to a Tukey test for significant differences between areas in the watersheds. A Pearson's correlation coefficient analysis was conducted to identify relationships between the measured soil properties. The statistical analysis was performed with *STATISTICA* Version 11, 2015 software. The SQ transformation and indices (PCA, regression equations, scoring functions) were performed in MATLAB Version 7, 2011 software with a PLS toolbox (Eigenvector Research). SQ indicators, SQI, and ANPP were tested for their levels of significance at $p = 0.05$ between the different areas.

3. Results

3.1. Soil properties

The results of the SQ properties in the different locations along the watershed are shown in supplementary Table S2. In all the *limans*, significantly higher SOM, TWC, and P values were found than in the *limans* compared to the other locations (Table 2). In addition, significantly higher HC and pH values were found in the upstream areas in all watersheds (Table 3). However, the watersheds are different from one another, due to changes in the geo-hydrological aspects, the location and the structure of the *limans*, and the different planted species (Fig. 3). In watershed number 1, significantly higher SH, EC, K, NH_4 and NO_3 values were found in the *liman* than in the upstream and downstream areas. In watershed number 2, significantly higher K and NH_4 values were found in the *liman* than in the upstream and downstream areas. In watershed number 3, significantly higher SH was found in the *liman* than in the upstream and downstream areas. In watershed number 4, significantly higher EC, NH_4^+ and NO_3^- values were found in the *liman* than in the upstream and downstream areas. In the watershed without *limans* (control), no significant differences were found in any of the soil properties, except for significantly higher HC and pH in the upstream area of the watershed. These results complement the findings from the upstream areas of other watersheds with *limans*. Fig. 3 showed the PCA result of the four watersheds and the control watershed, which shows the soil properties differences in each location.

3.2. Soil quality indices

The indices were developed from the results of the transformed soil property scores for all areas in the five watersheds. Fig. 4 presents the results of the PCA of all transformed soil properties for all watersheds, on factor plane 1 versus factor plane 2, based primarily on different areas in the watershed. The first four PCs had

Table 2
Soil quality properties that show significant differences in the *limans* in compered to the other locations along the watersheds with the sampling areas: (1) U: upstream area; (2) L: *liman* area; and (3) D: downstream area. Statistics include: average value, standard deviation, and significant differences between sampling areas in the watershed. The bold numbers refer to highly significant values ($p \leq 0.5$).

Location	SOM (%)	TWC (m/m)	P (mg/kg)
1_D	3.66 ± 0.97 b	5.79 ± 0.9 b	13.08 ± 3.43 c
1_L	**7.22 ± 1.23 a**	**8.01 ± 1.3 a**	**24.39 ± 5.74 a**
1_U	2.45 ± 0.3 c	3.5 ± 0.4 c	13.63 ± 2.54 c
2_D	4.51 ± 1.1 b	4.25 ± 0.3 b	14.84 ± 5.88 c
2_L	**7.55 ± 1.4 a**	**7.39 ± 0.6 a**	**36.63 ± 8.24 a**
2_U	3.62 ± 1.03 b	4.38 ± 0.4 b	28.68 ± 7.55 b
3_D	3.66 ± 0.7 b	2.46 ± 0.6 b	17.69 ± 6.12 b
3_L	**6.05 ± 1.02 a**	**4.44 ± 0.12 a**	**28.2 ± 6.4 a**
3_U	3.15 ± 0.33 b	2.46 ± 0.7 cb	18.46 ± 3.16 b
4_D	2.41 ± 0.36 c	2.37 ± 0.5 b	8.97 ± 3.24 b
4_L	**5.92 ± 1.07 a**	**3.61 ± 0.5 a**	**32.83 ± 5.23 a**
4_U	3.42 ± 0.7 b	2.22 ± 0.4 b	31.23 ± 5.04 a
Control_D	4.77 ± 1.0 a	2.42 ± 0.7 a	18 ± 4.56 a
Control_U	4.93 ± 0.5 a	2.84 ± 0.4 a	16.52 ± 5.26 a

*Abbreviations: TWC: total water content; SOM: soil organic matter and P: phosphorus.

Table 3
Soil quality properties that show significant differences in the upstream location compared to the other locations along the watersheds. The sampling areas: (1) U: upstream area; (2) L: *liman* area; and (3) D: downstream area. Statistics include: average value, standard deviation, and significant differences between sampling areas in the watershed. The bold numbers refer to highly significant values ($p \leq 0.5$).

Location	pH	HC
1_D	7.27 ± 0.12 b	0.083 ± 0.014 b
1_L	7.23 ± 0.07 b	0.075 ± 0.028 c
1_U	**7.42 ± 0.14 a**	**0.131 ± 0.023 a**
2_D	7.15 ± 0.03 b	0.089 ± 0.01 b
2_L	7.12 ± 0.09 b	0.089 ± 0.013 b
2_U	**7.59 ± 0.13 a**	**0.138 ± 0.06 a**
3_D	7.41 ± 0.07 ab	0.083 ± 0.016 b
3_L	7.21 ± 0.09 b	0.09 ± 0.008 b
3_U	**7.51 ± 0.16 a**	**0.101 ± 0.08 a**
4_D	7.39 ± 0.12 ab	0.118 ± 0.021 ab
4_L	7.23 ± 0.109 b	0.102 ± 0.016 ab
4_U	**7.54 ± 0.12 a**	**0.127 ± 0.02 a**
Control_D	7.44 ± 0.115 b	0.106 ± 0.023 b
Control_U	**7.58 ± 0.118 a**	**0.139 ± 0.018 a**

eigenvalues >1 and were included in the PCA (cumulative variance of 73.12%) (Table S3). The highest weighted variables under PC-1 were: TWC, HC, pH, EC, NH_4^+, NO_3^-, P, and K. In the second PC, SH and SOM had the highest weighted variables. The AGG had the highest weighted variables under PC-3, and PAC had the highest weighted variables under PC-4. Weights for selected variables were determined by the percentage of variation in the dataset explained by the first four PCs. The transformed data in PCs 1–4 were not highly correlated among themselves and were all included in the PCA ($R \geq 0.8$). These PCA results were used to calculate the SQI values for each location along the five watersheds according to Eq. (4).

The SQI results for all watersheds are presented in Fig. 5a, with standard deviations and significant differences (small letters). Significantly higher SQI values were found in all the *limans* compared to the downstream areas ($SQI_1 = 0.81$, $SQI_2 = 0.93$, $SQI_3 = 0.72$, $SQI_4 = 0.91$). No significant differences were found in the SQI values between the upstream and downstream areas within most of the watersheds and in the control watershed. However, significant differences were found in the SQI in watershed number 4, in the upstream and downstream areas ($SQI_{4\_U} = 0.76$ and $SQI_{4\_D} = 0.53$, respectively). Fig. 5b presents the results of the physical, biological, chemical soil properties in each location along the watershed. The biological soil properties showed higher changes in the *liman* areas, primarily representing an increase in the SOM (Fig. 5b). The control watershed shows no significant differences in the biological, chemical and physical soil properties between the upstream and downstream areas.

3.3. Aboveground net primary productivity

Fig. 6 shows the NDVI values by conducting transects along the upstream, *liman*, and downstream areas through the channel as a function of distance from the headwater. The black line shows the mean values for each location in transects along the watershed. Significantly higher NDVI values were found in all *limans* than in the upstream and downstream areas ($p \leq 0.01$). In watersheds 3 and 4, significant differences were found between the upstream and downstream areas ($p \leq 0.05$). In addition, a significant reduction in the total ANPP was found in the downstream area, compared to the downstream area in the watershed without *limans*.

The results of the annual ANPP in all watersheds showed significant differences between the upstream, *liman*, and downstream areas in the years 2014 and 2015 ($F_{(13,126)} = 35.57$; $p \leq 0.01$; $F_{(13,126)} = 20.81$; $p < 0.001$, respectively). A higher values of annual ANPP in the year 2015 than in the year 2014 was observed, and may be explained by rainfall differences between 2014 and 2015. A significant correlation was found between dry biomass in the years 2014 and 2015 ($R^2 = 0.52$, $p < 0.001$). Significantly higher annual ANPP values were found in all watersheds in the upstream areas than in the downstream areas. In addition, significantly higher annual ANPP values were found in all watersheds in the *liman* areas than in the downstream areas. However, only watershed number 3 had a significantly higher annual ANPP value in the *liman* area than in the upstream area. The annual ANPP values in the control watershed showed a similar trend with significantly higher annual ANPP values in the upstream areas than in the downstream areas. The results of the annual ANPP do not agree with the total ANPP shown in Fig. 6. There is a high heterogeneity at the patch scale in the annuals ANPP than in the total ANPP (using NDVI) in the watershed scale.

4. Discussion

The RHS is an ancient technique that has been used since the fourth century B.C. The Nabatean population created thriving settlements across the Negev by applying traditional ecological knowledge to harvest runoff and store water and to increase soil moisture storage to support agriculture mainly for tree plantation as orchards and for shade, as well as for grazing. There were approximately 700,000 acers of water harvesting farms built by the Nabateans of the Negev about 2000 years ago (Bruins et al., 1986; Prinz, 1996). These techniques are also relevant today for supporting dryland ecosystem services, such as food production, soil and water flow regulation and more. In the current study, we focused on the ecosystem effects of the *liman* system, a modern RHS. We investigated the effect of *limans* on their own locations, as well as on upstream and downstream areas, in Israel's Negev Desert, in relation to two ecosystem properties: SQI and ANPP. The RHSs exploit the natural runoff-producing areas (sources) and create runoff-absorbing areas in depressions (sinks), thus correspondingly modifying the SQI and ANPP (Figs. 5–7). We examined hypotheses concerning the effect of human-made resource-enriched patches in the downstream area and on the entire

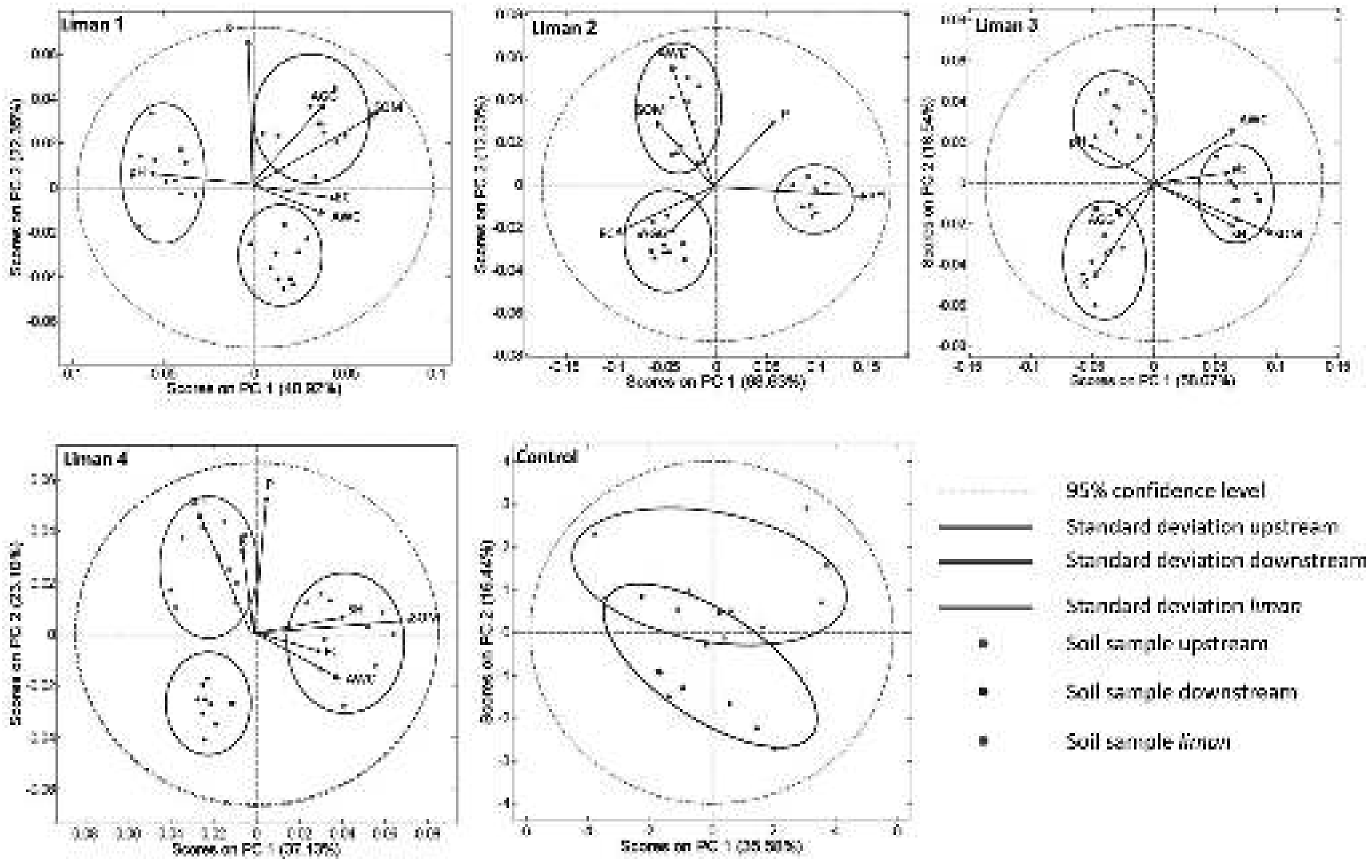

Fig. 3. A principal component analysis (PCA) of the five watersheds with all soil sampels overlaid with all soil properties, on factor plane 1 versus factor plane 2, based primarily on different areas in the watershed.

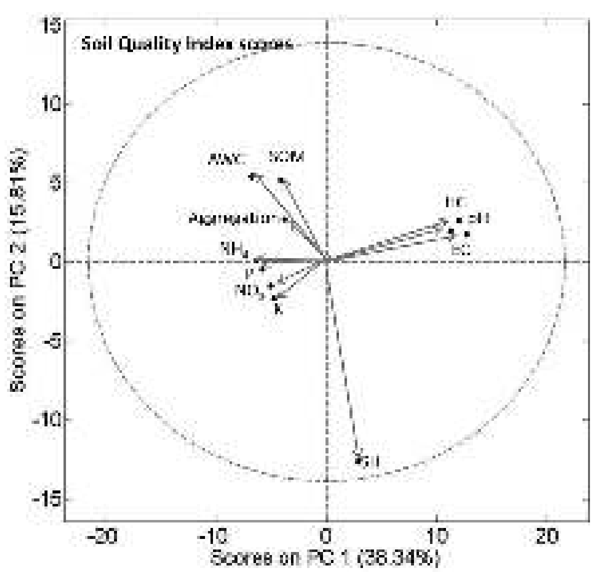

Fig. 4. The principal component analysis (PCA) of all transformed soil properties for all watersheds, on factor plane 1 versus factor plane 2, based primarily on different areas in the watershed.

watersheds. We found that there was an improvement in both indicators on the local scale (*liman*) and on the scale of the overall small watershed that includes the *liman*.

4.1. Small scale effect of limans on SQI and ANPP

The first hypothesis suggested that the construction of RHSs will result in increases in SQ, and in ANPP in the *limans*, in comparison to the downstream areas, due to water and nutrient accumulation that supports a system of trees and rich natural herbaceous vegetation. Our results agreed with the first hypothesis, showing a significantly increased SQI in all the *limans* compared to the upstream and downstream areas. It was found that in the *liman* areas, there were significantly high values of SOM, TWC, and P. The high values of SOM and TWC can be attributed to the accumulation of water and nutrients that are concentrated from large contribution areas into a small catchment area (e.g. Bruins and Ore, 2008; Hoekstra and Shachak, 1999a; Stavi et al., 2015). The plantation management may improve the SOM due to the addition of dry litter and organic matter from the trees and annuals plants. The additional input of P and SOM can be related to livestock grazing in the *liman* areas. These areas serve as grazing and resting locations for Bedouin-tended herds. Herbivore grazing, trampling, defecation, and urination affect soil P (Perkins and Thomas, 1993) and SOM (Smet and Ward, 2005, 2006). In addition, significantly higher total and annual ANPP values were found in all watersheds in the *liman* areas than in the downstream areas, which can support richer food webs of domestic and wild animals.

The second hypothesis suggests that the *liman* will shift the distribution of SQ and ANPP in the watershed scale. While in natural watersheds without *limans*, the highest SQ and ANPP would be found upstream, the *liman*, as a downstream component, shifts the peak of SQ and ANPP to the downstream area (Lavee et al., 1997;

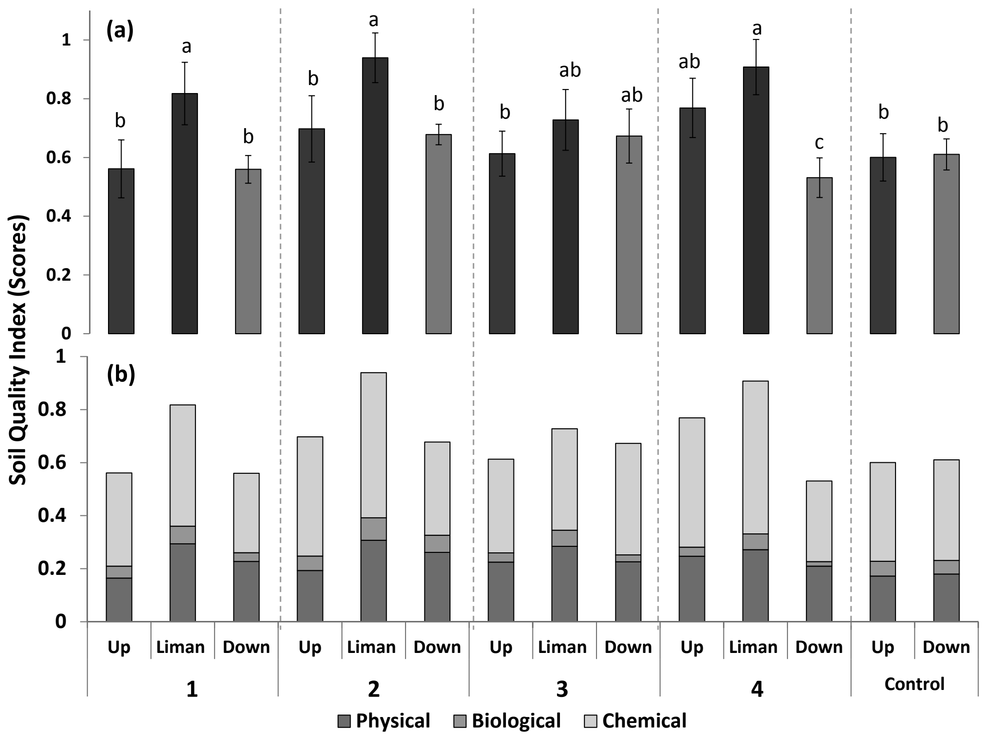

Fig. 5. (a) Soil quality index (SQI) scores for the different watersheds in the year 2015. Up: blue; *Liman*: red; and Down: green represent upstream, *liman* and downstream areas, respectively; and (b) SQI scores for the different watershed areas of the physical, biological, and chemical properties. Small letters above the error bars represent significant differences between treatments. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Yair, 2001). Studies have shown that in small natural rocky watersheds in the Negev, the geo-hydrological interactions in the relatively high percentages of rocky surface structure coverage, compared to the upstream soil volume, determine the rainfall-runoff-soil-moisture relationships (e.g. Olsvig-Whittaker et al., 1983; Yair and Kossovsky, 2002; Yair and Shachak, 1982). The main factors controlling upstream soil moisture are the high frequency runoff events, generated by the rocky surface even at low rainfall amounts, which infiltrate into the adjacent soil. In contrast, the downstream soil moisture is the result of a sink for infrequent but high magnitude runoff events in which a portion of the water infiltrates into the soil, some of the water leaks out of the watershed and most of it evaporates (Yair and Shachak, 1982). Construction of *limans* is showed an increase in the total ANPP, which may be related to redaction in water leakage from the downstream area of the watershed.

The soil moisture patterns, driven by rainfall attributes and their interactions with the geomorphologic properties of the rock to soil ratio, control the spatial patterns of producers, consumers and decomposers (Olsvig-Whittaker et al., 1983). This explains the pattern we found of high annual ANPP in the upstream area, in comparison to the downstream area, in all five watersheds. In addition, we found that the total ANPP was higher (represented by NDVI) in the upstream areas of watersheds number 3 and 4, in comparison to the downstream areas. However, no significant differences were found between the upstream and the downstream areas in watersheds number 1 and 2, and the control watershed. Our results indicate that low frequency but high magnitude runoff events in the downstream area can compensate for the high frequency, low magnitude runoff events typical to the upstream areas. We attribute the compensation effect to the geomorphological structure of the watershed. We found that adding a *liman* to the watershed always results in a productivity shift on the small watershed scale.

The SQI showed no significant differences between the upstream and the downstream areas in most of the watersheds (with the exception of watershed number 4). In the upstream areas, significantly higher values of pH and HC were found, which can be related to the geo-hydrological aspects of the upstream areas. The upstream area is characterized by a higher areal cover of limestone rock that may affect the soil pH and HC. However, significant differences between most of the soil biological, physical, and chemical properties were not found. As mentioned before, soil plays an important role in arid ecosystems as a water-storing element (Yair, 2001). The capability of soil to absorb and store water and nutrients is related to the soil volume, and its physical, chemical and biological properties. The differences in the ANPP values between the upstream, *liman*, and downstream areas are related to the geo-hydrological pattern (e.g., relative cover percentages of rocky and soil surfaces and soil permeability) (Hoekstra and Shachak, 1999b). Nutrient accumulation in the soil, as a result of rainfall redistribution by runoff, is another key factor in the determination of ANPP values in arid watersheds.

The third hypothesis suggested that degradation of SQI and ANPP will be found in the downstream areas in all watersheds containing *limans* compared to the watershed without *limans*, due to the dike's physical barrier that prevents continuation of runoff flow downstream. Results partially support this hypothesis, since no significant differences were found between the downstream areas in most of the watersheds containing *limans* and the watershed without *limans* in the annual ANPP. However, significant differences were found in the NDVI values between the downstream areas in all watersheds containing *limans* and the watershed without *limans* ($F_{(4,196)} = 23.85$; $p < 0.01$). These findings suggest that the total ANNP as NDVI representing ecosystem processes better than the annuals ANPP. This is due to high heterogeneity in

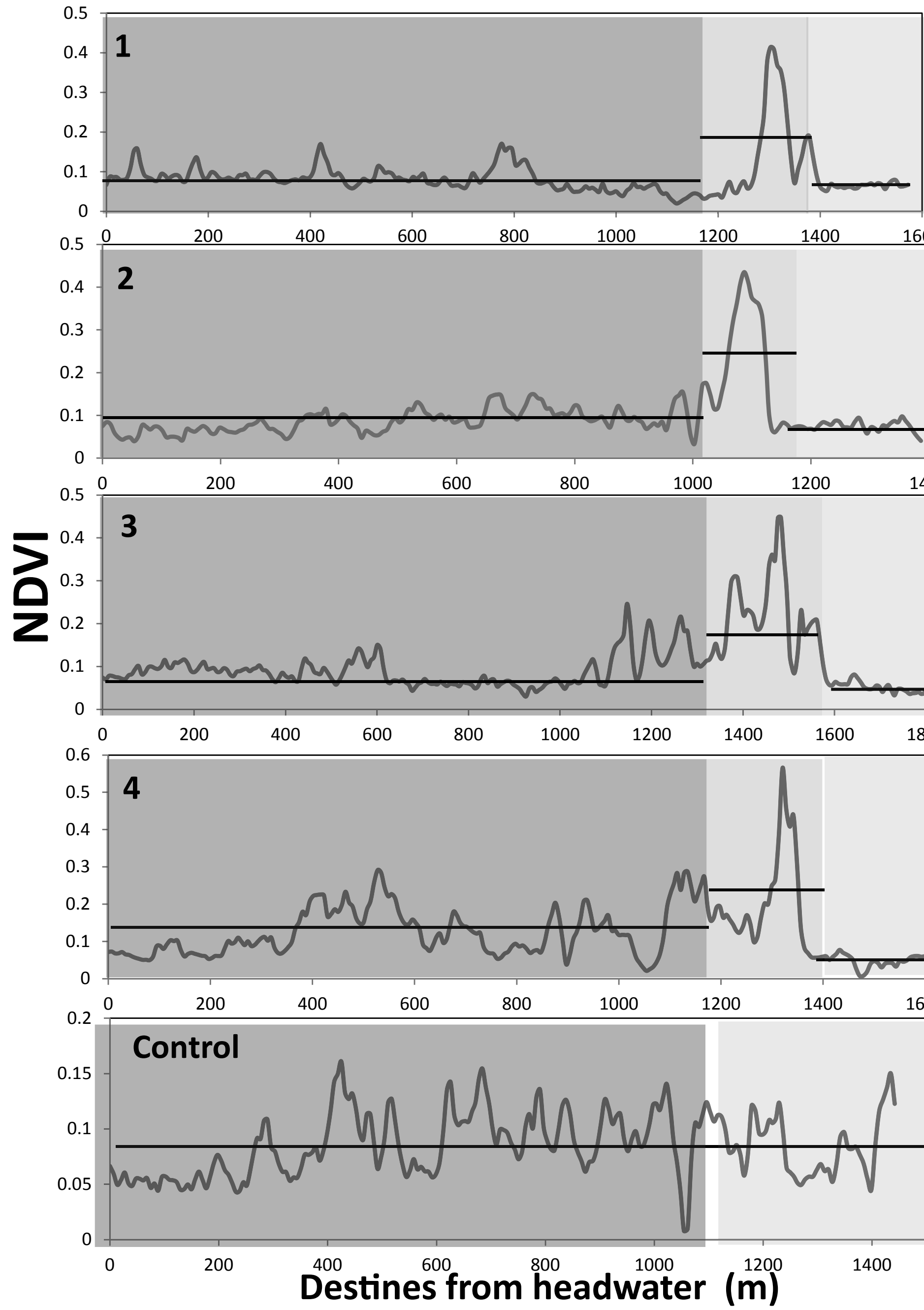

Fig. 6. Transects of NDVI values as a function of distance from the headwater and downstream, including the upstream, *liman* and downstream areas.

the annuals ANPP that is much larger than the total ANPP (NDVI values). In the current study, the relations between SQI, ANPP and biodiversity were not investigated. Future study should test the effects of *limans* on additional ecosystem aspects, such as biodiversity, functional and structural diversity, species recolonization, macro-climatic effects on species distribution and more in additional watersheds (Aronson et al., 1993; Bainbridge, 2012). These effects should be tested on a small watershed scale to evaluate the magnitude effect of the RHS.

4.2. Watershed scale effect of runoff harvesting systems

Beckers et al. (2013) refer to the size of the catchment on several implications and organizational aspects of RHSs. The location of a *liman* and its sink function should be considered from a whole watershed perspective (Lavee et al., 1997; Yair, 2001). A small catchments can use as a sufficient sources for agricultural production and tree plantation that tends to be moderate and manageable (Beckers et al., 2013). In larger catchments, such as that of a high-order wadis, runoff might turn into a flash flood, these larger catchments would result high peak flows that may reduce the efficiency of such systems. The size of the *liman* patches (sink) should be adjusted to the water volumes needed to sustain the ecosystem services to be provided by the RHSs. For example, if the aim of the *liman* construction is to provide ecosystem services associated with tree plantation, the tree number and the species

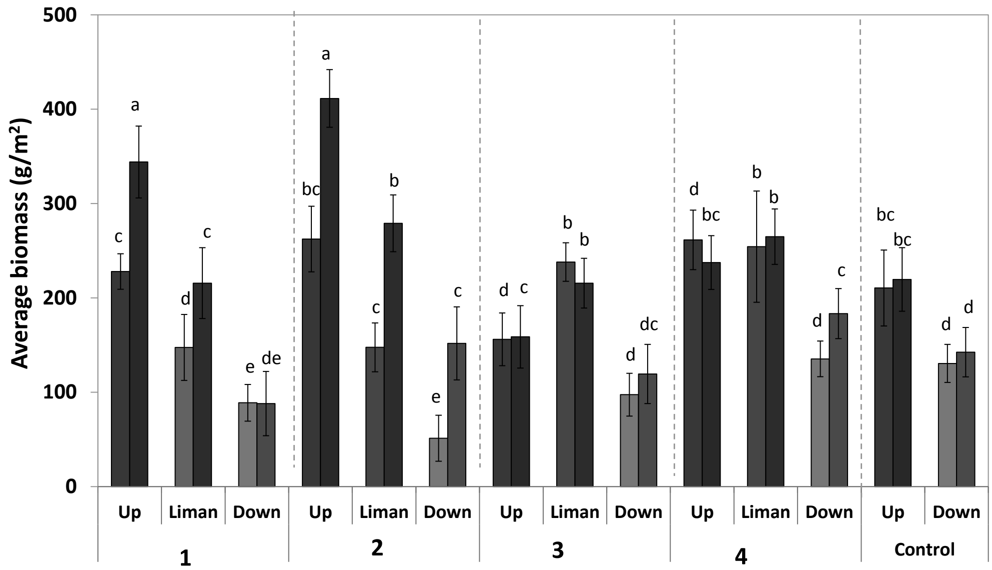

Fig. 7. The aboveground net primary productivity in the different watershed areas, average biomass measurements, and standard deviations for the years 2014–2015. Small letters represent significant differences between areas in the watershed for the different years. "Up" and "Down" stand for upstream and downstream areas, respectively.

planted in the enriched patches should be adjusted to the geo-hydrological regime in the watershed. However, if the objective is to enhance domestic animal production, then herbaceous species production should be the main concern. We found that the location of the *limans* in the downstream area may invert the distribution of SQ and ANPP in the watershed scale and otherwise would leak out of the system during runoff events. Our results show that the location of *limans* in lower alluvial reaches improves both SQI and ANPP as essential ecosystem properties, both on the local scale and on the overall small watershed scale.

RHSs is increasing the efficiency of water and improving water availability, thus used for supporting agricultural production or tree plantation (Printz and Malik, 2004). Our findings show a local increase in the SQI and ANPP within the *limans* in all watersheds compared to the downstream areas and an overall improvement on the small watershed scale, suggesting the possible enhancement of ecosystem services. Although RHSs are ancient techniques, their use in the new form of *limans*, a small-patch afforestation grove, is relevant today, for providing a bundle of ecosystem services to the local population, including firewood, production and shaded areas for humans and livestock. Grazing management is a huge challenge for dry agro-pastoral ecosystems while the annual productivity can be used for livestock grazing, thus reducing the grazing intensity and the vulnerability in the natural arid ecosystem. While these two processes result in a low productivity level, the net effect of the *liman* is an increase in soil fertility and primary production. This is especially important in light of global changes that are predicted to increase the intensity of droughts, as well as the increasing human pressure on drylands, including overgrazing and unsustainable agriculture (Dai, 2011).

5. Summary and conclusions

The success of RHSs in enhancing watershed fertility and its ecosystem services are related to complex geo-hydrological processes on the patch to the watershed scales. This study used the emergent properties of ecosystem processes, SQI and ANPP, to study the effect of integrating human-made water-enriched patches with the natural ecosystem and planted trees on a small watershed scale in a dryland. We found significantly higher soil organic matter, total water content, and phosphorus values in all of the *limans* compared to the other locations. Our results revealed significantly higher SQ and total ANPP values in the *limans* compared to the downstream areas, amplifying the overall watershed fertility, and suggesting the possible enhancement of ecosystem services. Our research demonstrates that in arid lands, integrating human design with nature is possible when knowledge on watershed ecology is available. This knowledge can produce a sustainable human-ecological management policy by enhancing ecosystem services in drylands.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jaridenv.2017.07.015.

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