Unusual Namibian fairy circle patterns in heterogeneous and atypical environments

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Abstract

Under homogenous habitat conditions, fairy circles are extremely ordered grassland gaps that are densely packed and that function as an extra source of water for the surrounding matrix vegetation. While the origin of fairy circles is still disputed, most of the research has so far focused on such typical habitat conditions where the fairy circles are almost round and have a nearly hexagonal pattern. However, Namibian fairy circles also occur under atypical habitat conditions where topographical heterogeneity or extreme aridity are forcing the circles to change their shapes and patterns. In this pilot study, we are describing some striking and new examples how shapes and patterns of fairy circles may change under such atypical environmental conditions. We emphasize the need to study fairy circles in disturbed catchment areas, mega circles in drainage lines, as well as soil-water budgets of irregularly spaced fairy circles in very arid locations. Furthermore, there is need to understand the formation of the very large mega circles and desertification fronts in flat habitat. Finally, we also discuss the potential role of abiotic drivers such as soil-crust formation in the vegetation matrix or aeolian erosion and subsequent de-rooting of grasses in forming unusual fairy circle shapes, sizes and patterns.

Keywords

Desertification front; eco-hydrology; fairy circles; heterogeneity; soil crust; wind erosion

Introduction

Namibian fairy circles are grassland gaps that have diameters from around 4 m in the Namib Sand Sea to 6 m in the Giribes Plains and 10 m further to the north in the Hartmann's Valley (van Rooyen et al. 2004). Analyses of satellite images revealed that fairy circles (FCs) have average life spans of approximately 40-60 years (Tschinkel 2012). Similar landscape-scale analyses also demonstrated that new born FCs increasingly appear after cumulative below-average rainfall years while FCs increasingly disappear after several years of above-average rainfall (Zelnik et al. 2015). These data, as well as the increase of FC size with aridity and the strong dependency on a very narrow climatic envelope of 50 - 150 mm mean annual precipitation (MAP) suggest that biomass-water feedbacks play a dominant role in forming FC shapes and patterns (van Rooyen et al. 2004, Cramer and Barger 2013, Getzin et al. 2015a,b Zelnik et al. 2015, Cramer et al. 2017, Ravi et al. 2017). While these studies support an abiotically driven origin of fairy circles, other studies attribute these gap patterns to a biotic origin such herbivory by ants or sand termites (Picker et al. 2012, Juergens 2013). Besides more explanations, the fairy circles have been also interpreted as being a vegetation anomaly resulting from abiotic gas leakage (Naudé et al. 2011) or from poisonous remains of *Euphorbia* shrubs (Meyer et al. 2015).

Except for the study by Meyer et al. (2015) which investigated the FCs in-between dune crests, all other studies focused their research on FCs primarily in topographically homogeneous environments. Under such typical conditions the densely packed fairy circles are extremely ordered and homogeneously spaced at the landscape scale (Getzin et al. 2015a,b). Thriving in such homogeneous habitats, the FCs typically function as a long-term water reservoir where even in the peak of the dry season the soil water content at a depth of a few dozen centimeters may be as much as five-fold higher than that under the surrounding matrix vegetation (Picker et al. 2012).

After decades of research, the fairy circles are still subject to a lively debate and their origin is a controversy (Sahagian 2017). Here, we therefore aim to broaden the scope of FC research by emphasizing the need to investigate pattern formation of vegetation gaps in heterogeneous and atypical environments. This is necessary because comparative studies of homogeneous versus heterogeneous habitats have shown that abiotic heterogeneity may have cascading effects on plant population dynamics (Getzin et al. 2008). The atypical environmental conditions will directly affect the function of abiotic drivers such as directed runoff water or heterogeneous soil-water diffusivity (Yizhaq et al. 2014). Since these conditions are principally interesting to study, we are providing here some descriptive examples of various unusual fairy circle shapes, sizes and patterns.

Materials and methods

In the first part, we provide four case studies of FCs for which we have measured their diameters and their volumetric soil water content (in %), using 20 cm long rods of a TDR (Time Domain Reflectometer). The field work was undertaken prior to the main rain season in early 2017 and thus represents dry-season results. For each study site in north-western and southern Namibia (*cf*: Table 1) we had chosen 20 FCs in which we took each time three TDR measurements inside the FCs. For comparison, we also took three measurements in the matrix location at circa 3 m distance away from the FC edge. From these data the minimum, mean, and maximum values were calculated (Table 1).

In the second part we highlight an additional case study from the Giribes Plains in north-western Namibia where we describe some unusual mega fairy circles of exceptionally large size which have been identified in Google Earth images prior to the field visit. We also report on the effect of wind erosion on gap formation and how it may contribute to enlarging fairy circles by the de-rooting of plants.

Results and discussion

Case study 1: High-density FCs in homogeneous habitat vs. low-density FCs in drainage valley - Giribes

This location in the Giribes Plains shows two contrasting environments - a typical homogeneous habitat with extremely regular FCs to the left and a heterogeneous habitat close to the right of the river bed (Fig. 1a,b). This is a prime example how the density and the strength of spatial ordering may decline in a disturbed catchment area.

Soil water content (SWC) measured in the dry season, was inside the high-density FCs with 1.5% significantly higher than the 1.1% in the matrix (Table 1). But in the disturbed drainage valley, SWC was with 0.9% inside the FCs very similar to the matrix (0.8%). The mean FC diameter there was lower (4.6 m) than in the high-density area (6.9 m) and grass biomass was also lower under degraded conditions in this drainage valley. We found several Himba cattle kraals just 100 m nearby and further away from that site. This area in the drainage valley likely has been constantly degraded over long time periods. Spatial trampling effects and consequently spatial heterogeneity in soil compaction, as well as the drainage valley itself, have probably caused these differences between the two sites. Such local habitat effects may indicate that under heterogeneous or disturbed site conditions, competition between the smaller grasses is lower, which may lower the difference in SWC between FCs and the matrix. In contrast, in homogeneous and undisturbed conditions, the larger and denser grasses take up more water and compete more strongly for soil moisture, hence the relative difference between higher SWC inside the barren FCs and the vegetated matrix becomes larger. Presumably, the disturbance in the drainage valley leads to a disruption in joint and symmetrically directed competition for soil moisture between the grasses, leading to overall less ordered FC patterns. At the same time, the smaller diameters of the FCs in the drainage valley could result from additional soil moisture during the short rain season that is beneficial to the grasses in this catchment area. Future research needs to disentangle these mutual effects of locally increased disturbance by ungulate grazing or trampling and topographical heterogeneity on fairy circle formation.

Case study 2: Chain-like, elongated mega circles along drainage lines - Giribes

In the southern part of the Giribes Plains it can be observed that fairy circles accumulate in a chain-like, tightly connected formation in drainage lines that go along a slope from north to south. These FCs can be called "mega circles" which are very special in that they are strongly elongated with the most extreme case being 32.5 m long but only 7.7 m wide (Fig. 1 c,d).

The mean SWC was inside the FC 2.8% but also 2.8% in the matrix vegetation (Table 1). This case study shows that the matrix and the FCs have similar soil moisture in the dry season if the FC pattern is not homogenous but heterogeneous or disordered - a result that we found consistently in Namibia. Only for these elongated FCs, we also measured soil compaction using a pocket penetrometer and 30 measurements inside a fairy circle and next to it in the matrix, respectively. We found that the soil in the matrix was much more compact than inside the FCs (mean values 2.3 kg/cm^2 vs. 0.6 kg/cm^2). The reason for the almost four times higher soil compaction in the matrix could be due to the presence of soil crusts which can be found outside of these elongated FCs (Fig. 1d). This interesting example shows that abiotic drivers such as soil compaction, directed water flow, and topographical heterogeneity are the main determinants of the shape and exceptionally large size of these unusual mega circles. Similarly, also for the fairy circles on gravel plains in the central Namib, the presence of physical or biological soil crusts in the matrix and resulting infiltration contrasts have been suggested as key determinants of FC formation (Ravi et al. 2017).

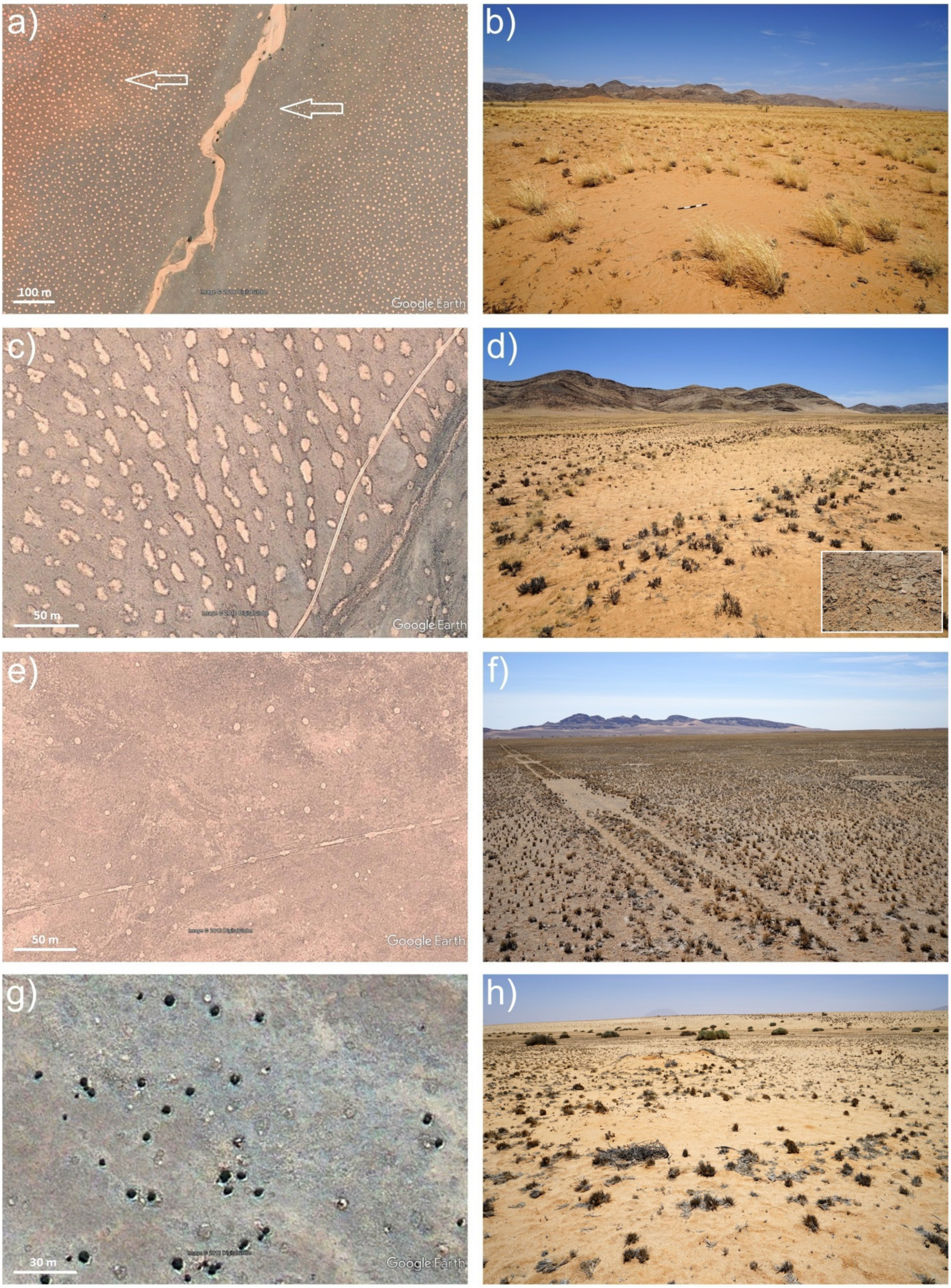

Figure 1. Fairy circles in heterogeneous and atypical environments. High-density circles in Giribes (a, left arrow) versus low-density circles (a, right arrow; b). The size of the scale bar in (b) is 0.5 m. Chain-like elongated mega circles on slope in Giribes (c, d) and soil crusts in matrix (d, inset). Disordered, low-density circles and road effects in Tsondab Valley (e, f). Disordered, low-density circles and *Euphorbia* shrubs near Garub (g, h).

Table 1: Measurements of fairy circle sizes and of soil water content (SWC) in FCs and matrix.

Location	Coordinates	MAP (mm)	min |mean | max FC Ø (m)	min | mean | max FC SWC (%)	min | mean | max Matrix SWC (%)
High-density circles Giribes	19°01’58’’S, 13°20’40’’E	≈ 100	5.7 | 6.9 | 8.8	1.3 | 1.5 | 1.8	0.9 | 1.1 | 1.4
Low-density circles Giribes	19°02’02’’S, 13°20’52’’E	≈ 100	3.8 | 4.6 | 5.4	0.6 | 0.9 | 1.3	0.7 | 0.8 | 1.1
Elongated mega circles Giribes	19°07’32’’S, 13°18’33’’E	≈ 100	5.4* | 16.9* | 32.5*	2.0 | 2.8 | 3.5	2.1 | 2.8 | 3.2
Low-density circles Tsondab Valley	24°03’12’’S, 15°46’24’’E	≈ 75	3.6 | 4.9 | 6.8	2.2 | 2.8 | 4.0	2.0 | 2.9 | 3.8
Low-density circles Garub	26°37’16’’S, 16°03’53’’E	≈ 50	2.6 | 3.7 | 6.9	0.5 | 1.5 | 2.0	1.4 | 1.7 | 2.1

*Values refer to the longest extent of the oval-shaped fairy circles.

Case study 3: Low-density circles and road effects - Tsondab Valley

In the Tsondab Valley in central Namibia fairy circles are disordered and show random distributions (Fig. 1 e,f). Here, annual rainfall is very low with c. 70-80 mm MAP. There was no significant difference between SWC in the FC as compared to the matrix (2.8% vs. 2.9%) and there was very low biomass in the matrix. Again, this example can be understood as atypical environmental conditions where very low biomass leads to very weak directed grass competition for soil moisture, which likely prevents the formation of hexagonally ordered gap patterns and the typical function of FCs as a long-term water reservoir. However, more field work is necessary to gain a better mechanistic understanding of causal processes.

In this area, road effects can be observed where elongated, up to 25 m long but only 4 m wide, FCs seem to accumulate along the car track (Fig. 1 e,f). These FCs are also disordered and show variable distances between each other, ranging from 5 to 50 m. We were unable to undertake TDR measurements along these tracks, because the 20 cm long rods could not be inserted into the soil due to a hard layer 5 cm below the surface. Such road effects where soil has been severely compacted can often be observed in various fairy circle areas (e.g. on the D845 road near Nubib Mountain; 24°41’54’’S, 15°58’14’’E). The soil compaction exerted by the weight of the car may last for many years and likely increases available soil water (Seely and Hamilton 1978) which may explain the linear formation of FCs there. Similar to the elongated mega circles along drainage lines, the micro-topography, soil texture, and associated soil-water budgets are determining the location and shape of these unusual fairy circles.

Case study 4: Low-density circles in inter-dune valley - Garub

In southern Namibia near Garub, fairy circles appear in low densities and heterogeneous distributions in the inter-dune valleys (Fig. 1 g,h). The FCs in this location have small diameters of around 3.7 m (Table 1) and their origin has been attributed to soil toxicity which results from the death of poisonous *Euphorbia gummifera* shrubs which grow next to the FCs and which have similar diameters (Meyer et al. 2015). These are very atypical fairy circles because soil moisture was significantly higher in the matrix (1.7%) than inside the FCs (1.5%). We observed many FCs which had an atypical convex shape with remains of accumulated sand, probably resulting from aeolian sand trapping of previous *Euphorbia* shrubs (Fig. 1h). Such raised heaps of sand dry out faster than the surrounding matrix soil which probably led to lower SWC inside the fairy circles. These FCs near Garub deserve further investigations since they demonstrate that the circular growth of grasses in the Namib is quite a common feature and the cause of fairy circles may not be limited to only one factor. However, these unusual FCs cannot explain the origin of fairy circles in most typical environments devoid of *Euphorbia* shrubs where much larger gaps prevail in highly ordered patterns and homogeneously across the landscape.

Case study 5: Mega circles, desertification fronts, wind erosion and tailed circles - Giribes

In the Giribes Plains on flat terrain (19°00'50''S, 13°19'08''E), very large mega circles can be found whose extent can be 23-26 m long (Fig. 2 a-c). Inside these FCs, large healthy *Stipagrostis* grasses are still growing. These large sizes of FCs which even merge with neighboring large FCs indicate that there is not enough water to sustain matrix vegetation. This is supported by the observation that in the Giribes often very large, continuous bare-soil areas can be found approaching the fairy circles (Fig. 2d). The continuous absence of vegetation indicates severe water stress and the phenomenon has been described as "desertification fronts" that expand into uniform vegetation (Zelnik et al. 2017, Meron 2018).

Besides a lack of water, wind erosion and the de-rooting of grasses at the gap periphery is another abiotic driver that may facilitate the enlargement of fairy circles. This is particularly the case in the Giribes Plains which have strong winds, leading to sand erosion and to very concave fairy circle depressions. We noticed numerous individual grasses in FCs where plants bended over and finally died by this de-rooting aeolian process (Fig. 2e,f). Therefore, we counted the number of de-rooted individual plants at the peripheries of 20 fairy circles. We found that in each circle on average nine plants of the peripheral belt were affected by de-rooting with a found maximum of 14 plants in circles. Notably, this counting only addressed grasses that showed no effect of termite influence (i.e. the black tapetum around the plant basis). This is an important observation because it shows that abiotic erosion processes induced by wind can kill the plants especially along the inner periphery of fairy circles and this process may affect the size of the circles.

Finally, we also present so-called “tailed circles” (coordinates: 19°00’29’’S, 13°19’25’’E). These can be often found in the Giribes Plains near the desertification fronts and elsewhere. They are characterized by tall grasses building the tail which ends in the open fairy circle (Fig. 2g, h). The tall grasses at the tail indicate a surplus of water which is similar to the wider road effects. Possibly, the tails have been initiated by ungulates, water-flow, and erosion within these channels.

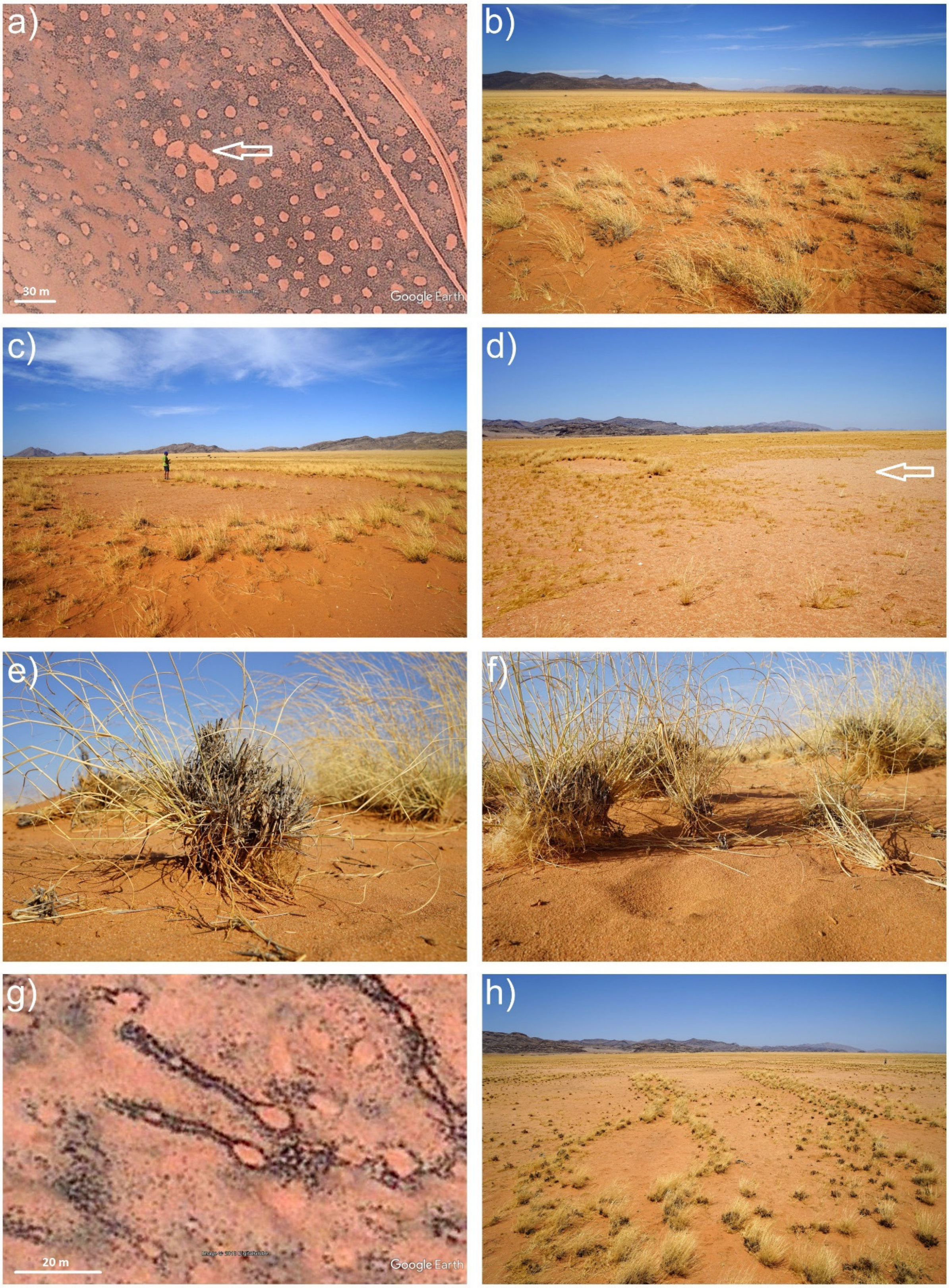

Figure 2. Mega circles, desertification fronts, and tailed circles in the Giribes Plains. Extent of a 26 m long mega circle with remains of *Stipagrostis* grasses (a, arrow; b). Same as (b) but a 23 m mega circle (c). Desertification front (arrow) expanding towards a fairy circle (d). Wind erosion causing de-rooting and death of *Stipagrostis* grasses at the edge of fairy circles (e, f). Tailed fairy circles with tall grasses along the tail (g, h).

Summary

One clear result of our pilot study is the observation that the FCs function also in the dry season as a long-term water reservoir, provided they attain a high density and strong spatial order as in typical homogeneous habitat conditions. However, if the FCs have a low density and low spatial order or they are affected by heterogeneous topography such as drainage lines, they seem to lose their functioning as a water reservoir in the dry season. Possibly, the strength of soil-water diffusivity feedback under spatial heterogeneity (Yizhaq et al. 2014) is too low to allow for a highly symmetrical pattern formation.

Our unique case studies of the investigated new fairy circle patterns are intended to inspire future research and to point to the importance of studying vegetation patterns being subject to heterogeneity effects and other atypical environmental conditions alike. In conclusion, we emphasize the need to study in more depth the abiotic drivers of fairy circle formation like soil crusts and soil texture (Ravi et al. 2017), topographical heterogeneity, and wind or water erosion.

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