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# Effects of artificial light on flowering of foredune vegetation

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*Abstract.* The impact of ecological light pollution involves alteration of periods of natural light, a fact that has proven effects on ecosystems. Few studies have focused on the impact of this pollution on wild plant species, and none on coastal dune plants. Many coastal dunes and their plants are adjacent to tourist areas, and these might be affected by light pollution. Such is the case of the Natural Reserve Dunas de Maspalomas (Gran Canaria), where some individuals of the plant species *Traganum moquinii*, located in the El Inglés beach foredune zone, are affected by light pollution. This study examines the effect of light pollution on the flowering process and, by extension, the reproductive cycle of these plants. Plants located closer to high artificial illumination sources receive ~2,120 h/yr of intense light more than plants located furthest from those artificial lighting sources. Parts of the plants of *Traganum moquinii* exposed directly to the artificial light show a significant decrease in the production of flowers, compared to the parts in plants in shade, and to the plants more distant from artificial lights. In consequence, plants exposed more directly to artificial light have a lower potential for seed reproduction. The spectrum of artificial light also affects the plants, and light between 600 and 700 nm primarily affects the reproductive cycle of the *Traganum moquinii* species. The implications for the ecological and geomorphological functioning of the dune system are discussed, because this species plays a decisive role in the formation of foredune zones and nebkhas in arid dune systems.

*Key words: flowers; foredune; light pollution; nebkha; reproductive cycle;* Traganum moquinii.

## Introduction

The term "light pollution" refers to excessive or intrusive artificial light caused by bad lighting designs (Gallaway et al. 2010). This term includes the sum of all adverse impacts of artificial light, although it can be considered as "ecological light pollution" when the natural patterns of light and dark are altered in ecosystems by the emission of artificial light (Longcore and Rich 2004). This is mainly produced by outdoor night lighting facilities (Herranz 2009).

Night light pollution has grown exponentially over the natural levels of night illumination provided by moonlight (Falchi et al. 2011, Gaston et al. 2013). This exponential growth is due to the development of electric lighting technologies (Gaston et al. 2013), so that, as human communities have developed, artificial light has been disturbing the natural cycles of light, hence influencing biological systems.

The effects of light pollution on the environment are beyond doubt (Longcore and Rich 2004, Masahiro and Koichiro 2004, Wang et al. 2009, Bennie et al. 2016), since there is evidence that artificial light alters certain processes, including primary productivity (Gaston et al. 2013). Most studies are heavily weighted toward higher vertebrates and invertebrates, with an information gap in many other aspects of natural plants (Gaston et al. 2013, Bennie et al. 2016, 2018*a,b*).

Light pollution can alter species composition as well as the balance of cover and biomass between plant species in natural vegetation communities (Bennie et al., 2018a). A dark period is important for flowering plants as this affects productivity, although species respond differently to changes in the periods of light and dark. The first studies on the effects of light on plants were developed early for species with commercial interest, in order to ascertain whether certain changes in photoperiods increased the production of certain parts of plants. These studies primarily focused on the floral parts. From these studies, it appears that short-day plants flourish

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when the dark period exceeds a critical value and long-day plants flourish when the length of the dark period is less than the critical value (Tournois 1912, Devlin 1980, Taiz and Zeiger 1998). As an example, if hemp plants are exposed to short photoperiods (6 h), they flourish, whereas if the photoperiods are long, they remain in a vegetative state (Tournois 1912).

In the investigation of photobiological reactions, it has become a standard practice to determine the influence of particular bands of the electromagnetic spectrum on certain processes (Devlin 1980). Moreover, the most effective wavelengths to inhibit flowering are between 600 and 680 nm (orange-red), with a maximum located at about 640 nm (Borthwick and Hendricks, 1960). Similarly, light enriched in the 500–600 nm band (green) affects the growth and morphological characteristics of some plants. For example, *Zantedeschia aethiopica* produces flowers with longer peduncles (Casierra-Posada and Rojas, 2009). Experiments have also been conducted with certain fruits, such as tomato, showing that they have a higher concentration of lycopene in the exocarp of immature plants exposed to short pulses of UV-C and red light, when compared to individuals exposed to the cycle of natural light (Liu et al. 2009). However, few studies analyze the effects of light pollution on plant species, which are not of commercial interest.

The area of land with environmental protection has increased worldwide in recent decades. The proximity of some of these areas to urban centers may cause some conditions of light pollution. Such is the case of the Natural Reserve Dunas de Maspalomas (Gran Canaria), where some individuals of the plant species *Traganum moquinii*, typically forming nebkhas (discrete dunes formed in plants) located along El Inglés beach, are exposed to lights that illuminate a tourist complex including a shopping center and promenade along the beach. It is possible that the *Traganum moquinii* plants located in the vicinity of the shopping center (Fig. 1 down), have a smaller number of flowers, especially in the branches oriented towards the lights that illuminate the promenade compared to plants unaffected by the lights.

Considering the possibility that artificial light may be affecting *T. moquinii* behavior, the aim of this work is to determine if the plants exposed to the artificial light are affected in their reproductive potential. Thus, the following specific aim is proposed: to determine if the extent of the exposure of *Traganum moquinii* to artificial light at El Inglés beach affects the flowering process and the reproductive cycle of these individual plants. In order to answer this, three objectives were established: (1) to collect field data in order to establish if the plants, or parts of the plants exposed to the artificial light, produce a smaller number of flowers; (2) to establish if, under controlled conditions, exposure to a greater period of artificial light alters the reproductive potential of the seeds of this species; and (3) to ascertain whether some wavelengths of the visible light spectrum affect the reproductive cycle of this species.

### *Study area*

*The Maspalomas dunefield.*—The transgressive dunefield of Maspalomas, at 360.9 ha, is located in the south of the island of Gran Canaria (Canary Islands, Spain; Fig. 1 upper row). This dune field covers a deltaic plain, which originated during the Quaternary, with marine and alluvial deposits related to sea level oscillations (Hernández Calvento 2006, Pérez-Chacón et al. 2007). A variety of dunes occur on the dunefield, including nebkhas, barchan dunes, barchanoid ridges, transverse ridges, echo dunes, sand sheets, interdune depressions, and deflation surfaces (Hernández Calvento 2006, Pérez-Chacón et al. 2007). On the eastern seaward margin, El Inglés beach, the foredune zone is characterized by a nebkha field with a typical hummocky morphology. The dominant plant forming nebkha is *Traganum moquinii* (Hernández-Cordero et al. 2012).

The climate is arid, with an average annual rainfall of 81 mm, but with large annual and interannual rainfall variability, and an average annual temperature of 21°C (Hernández Calvento 2006, Smith et al. 2017).

The natural characteristics of the dunefield have led the government of the Canary Islands to declare it a special nature reserve. However, at the same time, this system is a prime tourist attraction. In recent decades, the beach-dune system of Maspalomas has experienced significant environmental changes due to tourism such as the expansion of deflation areas, lowering of the height of the dunes, movement of the first line of free dunes downwind with respect to the backshore, fragmentation of the El Inglés' nebkha field (foredune zone) and declining populations of *Traganum moquinii* (Hernández Calvento 2006, Hernández-Cordero et al. 2012, 2018, Cabrera-Vega et al. 2013*b*, Peña-Alonso et al. 2015).

Traganum moquinii.—The habitat of *Traganum moquinii* Webb, from Lems (1960) is coastal sand, where it occupies the strip along the backshore, although populations or individuals can be found at some distance from the coast, but, in general, not further than a few hundred meters. Its worldwide distribution spans the northwest coast of Africa, from Morocco to Mauritania, as well as to the archipelagos of the Canary Islands and Cape Verde (Santos 1993, Géhu and Biondi 1998, Hernández Cordero et al. 2008). In the Canary Islands, it appears in the eastern islands, as well as in Tenerife and La Gomera. It constitutes, therefore, the first band of vegetation existing in the main dune systems of the Canary Islands (Corralejo, at Fuerteventura; El Jable, at Lanzarote; different large sand deposits (jables) of La Graciosa; and dunes of Maspalomas, in Gran Canaria). Burial by sand stimulates its growth (Ley et al. 2007, Viera-Pérez 2015).

The vegetative cycle of *Traganum moquinii* has three distinct stages: flowering, vegetative growth, and rest. In Maspalomas, these stages may overlap to a degree with transitions between them. The fruiting stage is

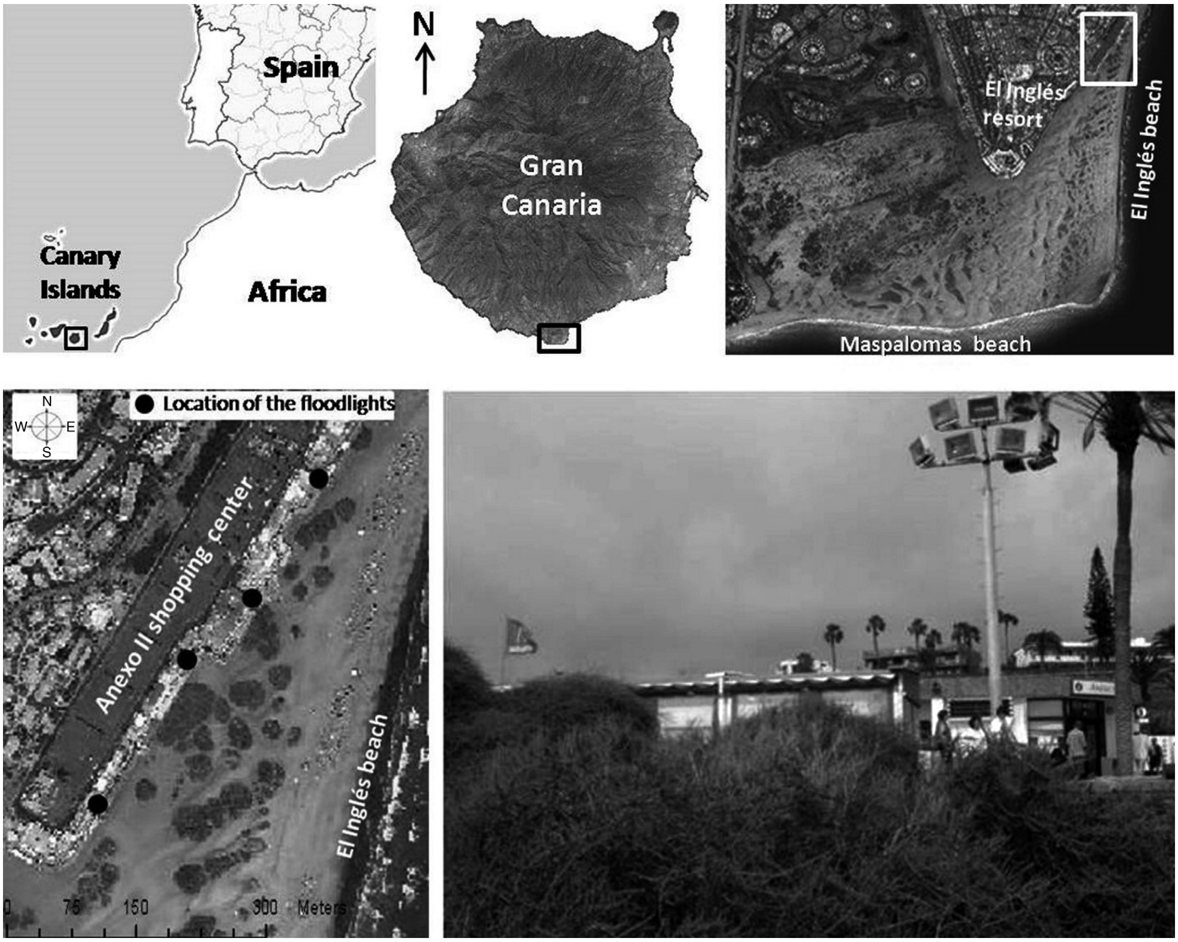

Fig. 1. Location of the Maspalomas dune field (upper row). Location of floodlights in the shopping center (lower left) and *Traganum moquinii* plants close to the Anexo II shopping center and a floodlight (lower right).

temporarily parallel to the flowering stage, so fruits can be found throughout the year. *Traganum moquinii* is able to emit more than 100,000 flowers per cubic meter of canopy. The period that the seed needs to reach full maturity is around 220 d (Viera-Pérez 2015).

## Methodology

The methodological design was carried out in two phases: field observations and a controlled experiment. During the field observations, the intensity and duration of artificial light along the beach was determined in order to characterize the luminescence during the night time. Also field observations were used to determine to what extent the exposure of *Traganum moquinii* to artificial light at El Inglés beach affects the flowering process and the reproductive potential by seed of these individual plants. The controlled experiment was carried out to determine to what extent the exposure of *Traganum moquinii* to artificial light under controlled conditions affects the flowering process and the reproductive potential by seeds of these individual plants. In this phase, an attempt was made to determine if certain light wavelengths affect the flowering process of these plants.

Field observations were carried out to determine the intensity of light in the field, utilizing a light meter ROBIN RT 24 (Robin Electronics Ltd., UK) and a GPS locator. The light meter was held horizontally at a height of 1 m above the ground, facing magnetic north. A total of 300 data collections were performed, with a higher density in the vicinity of the light sources and lower density with increasing distance from the shopping center (Fig. 2 top). The illumination was observed from sunset to 01:00, the same period of time the floodlights are on (Municipality of San Bartolomé de Tirajana, *personal communication*). A solar calendar was used to determine the time of exposure of plants to artificial lights, taking into account the geographical location of the study area.

To determine how the exposure of *Traganum moquinii* plants to artificial light affects their flowering process and their reproductive potential by seeds in natural conditions, three sectors along El Inglés beach were

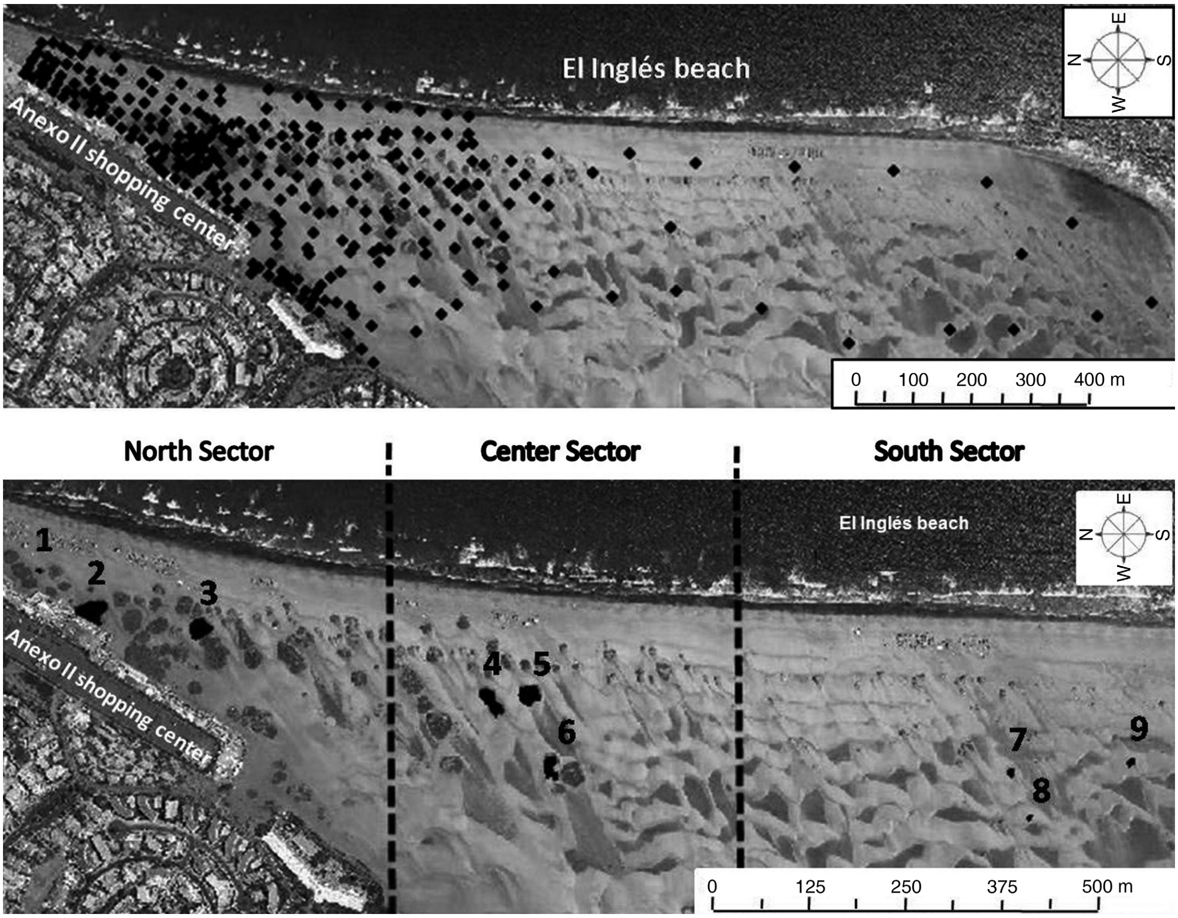

FIG. 2. Location of the point where fieldwork was performed (top). Sectors established along El Inglés beach: north, center, and south (bottom).

established: north, center, and south (Fig. 2 bottom). The samples of the plants were extracted from each of these sectors. In order to obtain the same volume of vegetative material and to minimize damage to the plants during collection, a removable device was designed (see Appendix S1: Fig. S1 for details).

To determine the effect of artificial light on flowering of *Traganum moquinii*, six discrete plants were randomly selected in each sector. Two samples were collected in each one of the plants, except in those located in the northern sector, where two samples were collected with direct exposure to artificial light, and two in the shaded zone. The samples were transferred to the laboratory, where the flowers were counted.

For the statistical analysis of the data, linear mixed effects models were used (Eq. 1):

$$y_{ij} = \mu + v_i + b_j + \varepsilon. \qquad (1)$$

For comparing the differences between the unlit sectors of the north, center, and south, $y_{ij}$ is the number of flowers in plant $j$ of the sample taken in sector $i$, where $i \in$ {North, Center, South}, and $v_i$ is the effect of sector $i$; $v_i$ is a fixed effect because our objective is to compare these three given sectors; $b_j$ is the effect of the plant $j$ in that sector. As individual plants have been chosen at random in each sector, we will consider $b_j$ as a random effect, since we are not interested in comparing these specific subjects with each other, but rather to take into account the variability they bring to the model. $\varepsilon$ is the residual term, which is assumed to have a normal distribution of mean 0 and standard deviation $\sigma_\varepsilon$.

For comparing the non-illuminated area with the illuminated area in the northern plants, $y_{ij}$ is the number of flowers in lighting condition $i$, $i \in$ {Light, Darkness} measured in plant $j$ of the sample, and $v_i$ is the effect of the lighting condition Yes/No. The rest of the terms are defined in a similar way as in the previous model above. Details of the adjustment can be found in Pinheiro and Bates (2000). The adjustment was carried out with the nlme package of the statistical software R, version 3.3.0. (Pinheiro et al., 2017; R Core Team, 2017)

The existence of differences between sectors or between lightning conditions was assessed by applying

ANOVA tests to these models. When significant differences between means were detected, Tukey tests were applied to classify the differences according to the sector. Finally, for validating the application of ANOVA, Levene and Shapiro-Wilk tests were used to verify that the conditions of homoscedasticity (equality of variances in the groups compared) and normality were fulfilled.

For the controlled experiment, the first step was to determine whether, under controlled conditions, an increase in the number of hours of light altered the natural cycle of the plants as compared to the number of hours of the natural light cycle. This was intended to minimize the effect of other possible factors that could be producing this alteration in natural conditions. The second step was to ascertain if certain wavelengths of the visible spectrum produced a greater alteration in the natural cycle of this species. For this, an experiment was carried out under controlled conditions, far from the influence of any other human-induced or natural (e.g., substrate) factors. Five treatments were designed, with 12 replications, in an open-air laboratory, in the coastal municipality of Telde (Gran Canaria), where the IOCAG facilities are located.

The floodlights along the promenade are 1000 watts sodium foci with peak illumination in the yellow light strip; thus, the experiments were designed with this level in mind. The treatments consisted of (1) not applying any extra light, leaving the group of plants exposed only to the natural light cycle (this group was called the reference group); (2) applying extra-white light (400–700 m) from sunset to 01:00 of the following day; (3) applying extra blue light (400–500 m) from sunset to 01:00; (4) applying extra green light (500–600 m) from sunset to 01:00; and (5) to applying extra red light (600–700 m) from sunset to 01:00. Extra light was applied to plants that were also exposed during the day to the natural light cycle. The experiment was carried out between 1 November and 30 April. The intensity of the extra light was the same as that which had been identified in the field, in the vicinity of the lampposts, during the first phase (190 lux in the zenith and 160 lux in the furthermost points). These differences in intensity determined that only twelve replications could be made, so that all of them received a value of 190 lux.

Individual plants that received the extra light treatment were exposed to an average of 6 h of light per day (1,125 total hours throughout the experiment) more than the reference group. Plants were separated by white wooden boards to avoid any influence from each other. A total of 60 plants were selected randomly from a group of more than 200 healthy plants, which were grown by asexual reproduction five months earlier outside with vegetal material from terminal buds. The plants, about 8 cm in length, were planted in individual containers, 40 cm high and 13 cm in diameter, with sand substrate and irrigation by capillarity action. They were, therefore, young plants that had never flowered, so at the beginning of the trial, they did not exhibit any flowers.

An analysis of variance was used to compare the mean number of flowers under different conditions. Shapiro-Wilk and Levene tests were used to verify that the conditions of normality and homoscedasticity were fulfilled and validate the model. A Tukey test was applied to determine under which lightning conditions means were different from each other.

## RESULTS

### *Intensity and duration of extra light*

The results of the field observations of the light intensity form a digital lighting model made from the generation of an irregular triangle network (TIN) by vector interpolation (Fig. 3). As noted in *Methodology*, lighting values above 200 lux are reached in the vicinity of the promenade. In the controlled experiment, the *Traganum moquinii* plants were subjected to light similar to those located close to the promenade, but with values slightly lower at 190 lux. These were far from the values of around 0 lux detected in the most remote areas away from the promenade. In the middle of the dune field, the values were below 0.5 lux. There are areas with values lower than their surroundings because the dunes induce shadows in the interdune areas.

Fig. 4 illustrates the results related to the duration of the extra illumination during a year. The duration (in h/d) to which the plant specimens are exposed has been reversed, considering from sunset to 01:00. The sum of the daily hours of extra light that the plants receive is 2120 h/yr.

### *Flower production*

The only area where data is available with and without artificial illumination is in the northern sector since there are portions of plants in that sector that are always in shadow. The three sectors were first compared using only the samples obtained where there was no direct illumination from artificial sources (i.e., unlit plants, or parts of plants in shadow; Fig. 5 and Table 1).

The analysis of variance applied to these data using the mixed effects model (*Methodology*), which considers the individual plant as a random factor and the sector as a fixed factor, shows a significant effect of the sector ($P = 0.0028$). Post hoc Tukey tests show that the central sector has a higher average number of flowers than the south and north sectors ($P = 0.0002$ and 0.0006, respectively), while the southern and northern sectors do not show significant differences ($P = 0.8927$).

For the northern sector, where parts of the plants are directly illuminated or in shadow (unlit), we analyzed the effect of light, taking into account that two samples (lit, or in shadow) have been obtained from each individual plant (Table 1).

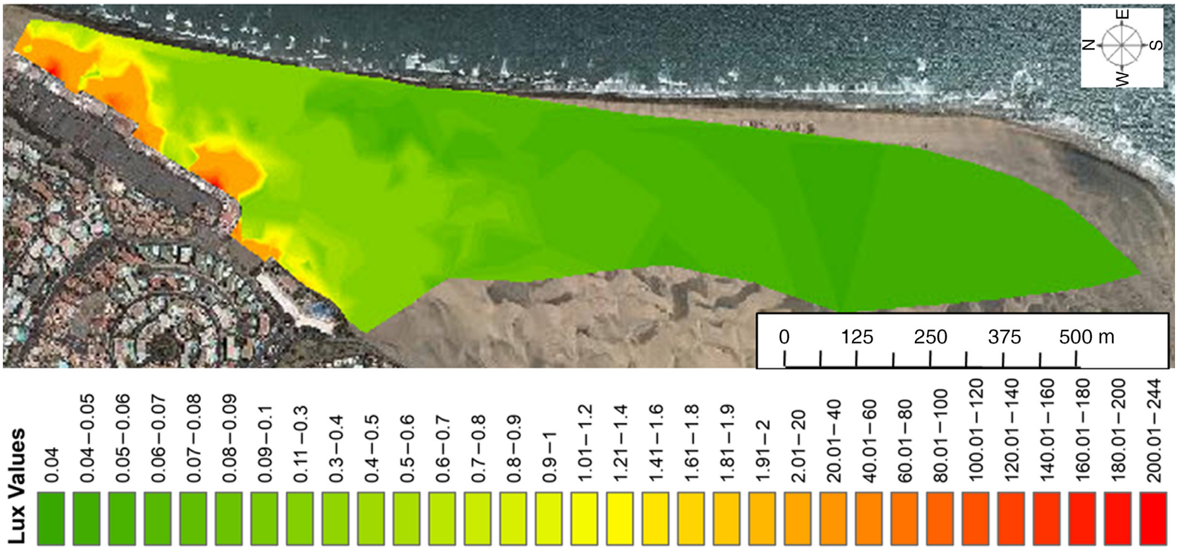

FIG. 3. Digital model of the light ranges at El Inglés beach.

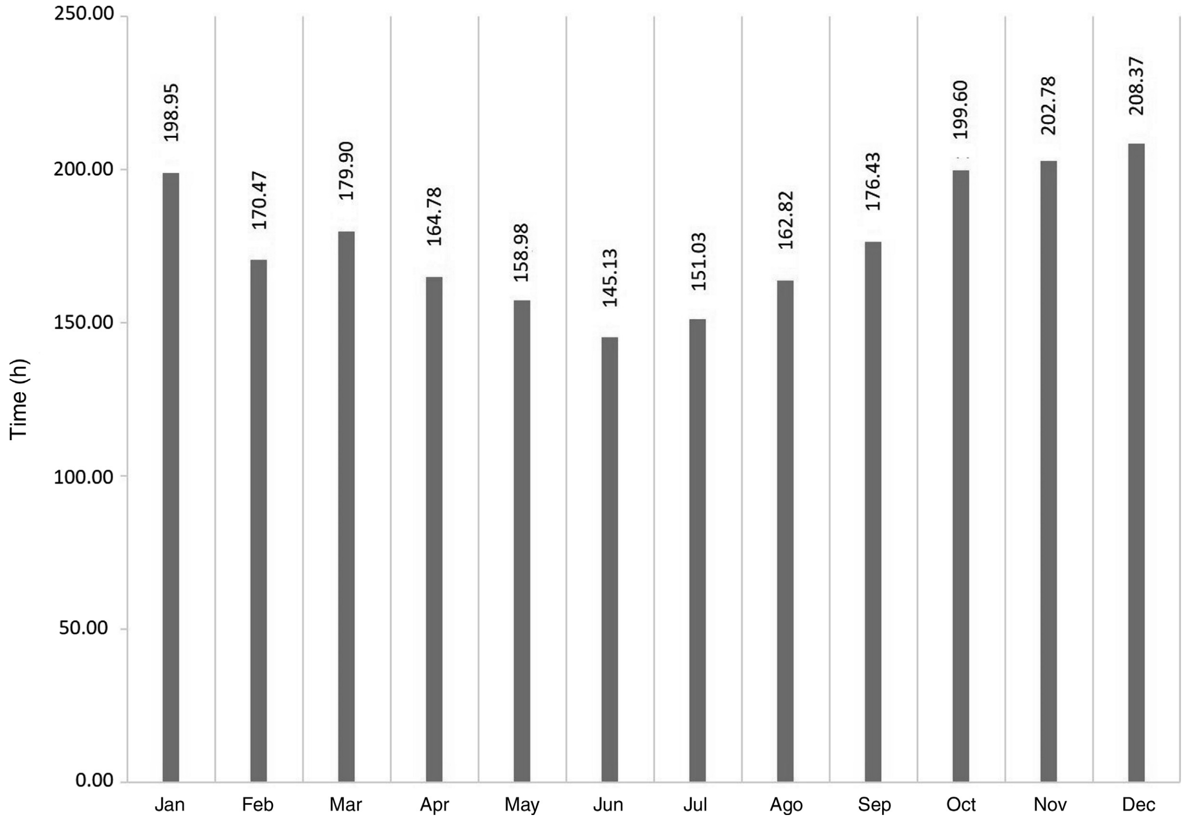

FIG. 4. Duration of the extra illumination during a year.

We analyzed these data also using a mixed effects model, considering individual plants as random effects and the presence of artificial lighting as the fixed effect. The effect of the subjects is random because we are not interested in comparing each subject with the others, but to take into account the inter-individual variability, also using each subject as their own control. The ANOVA test of the model shows a significant difference

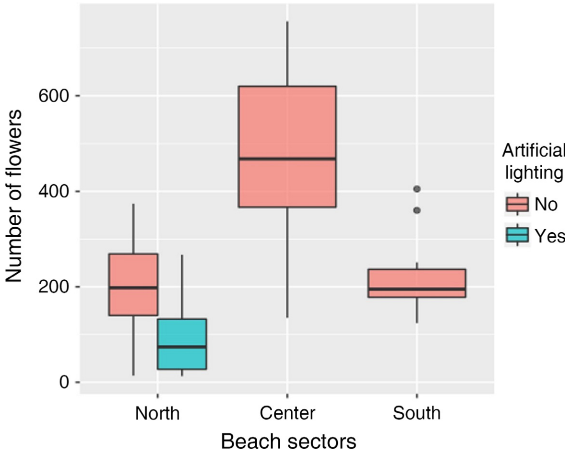

Fig. 5. Flower production in *Traganum moquinii* plants in the three sectors along El Inglés beach. Box plot components are mid line, second quartile (Q2), median; box edges, first quartile (Q1) and third quartile (Q3); whiskers, max(Q1-1.5 IQR, min[observed values]) and min(Q3 + 1.5 IQR, max [observed values]), being IQR=Q3-Q1; and points, outliers

($P = 0.0002$) between the average number of flowers depending on whether the plant is directly exposed to artificial lighting or not. The number of flowers is higher when plants are not exposed directly to artificial light.

### *Effects of differing light conditions*

Fig. 6 shows a box plot representing the distribution of the number of flowers subjected to the five experimental light conditions. The average number of flowers under the different conditions (Table 1, right) was compared by analysis of variance. Data were previously transformed to a logarithmic scale so that the conditions of normality and homoscedasticity necessary to proceed with the ANOVA test were fulfilled. The ANOVA showed significant differences between light conditions ($P = 0.0007$). To determine under which conditions these differences occur, a post hoc Tukey test was performed (Fig. 7). There is a significant difference between the red light and the reference value ($P = 0.0014$), between the target and the reference value ($P = 0.0173$) and between the red and the green lights ($P = 0.0143$). Blue does not show significant differences with any other colors.

## Discussion

This study demonstrates that light pollution affects *Traganum moquinii* plants in the foredune zone of Maspalomas (Canary Islands), inducing a decrease in their flowering production. The plants located in the northern sector, closer to the lights of the promenade, are more exposed. These plants are exposed to extra light during all the year increasing their annual exposure to 2,120 h of additional artificial light. Values around 190 lux were measured in this northern sector. To understand these values, consider that the full moon in an overhead position and on a clear night can induce a luminescence around 0.15 lux (Galadí 2009).

The fact that the parts of *Traganum moquinii* exposed to artificial light have a lower number of flowers could be related to this extra lighting factor, or not. The possible existence of other factors could also induce an alteration in the biological cycle of these plants. However, no factors have been found in the current literature to provide another explanation for the phenomenon. Pérez-Chacón et al. (2007) and Ministerio de Medio Ambiente (MMA) (2007) analyzed substrate samples in the study area and found no significant differences in texture and composition between the samples located in the north and those located in the rest of this system. The

Table 1. Average number of flowers per individual plant in each sector.

| | No. flowers | | |
|---|---|---|---|
| Conditions | By sector† | By lighting condition‡ | By light color group |
| Sector | | | |
| North | 198.3 (112.4) | | |
| Center | 474.2 (169.8) | | |
| South | 223.6 (82.07) | | |
| Lighting | | | |
| No | | 198.3 (112.4) | |
| Yes | | 96.75 (88.25) | |
| Light color | | | |
| Reference | | | 11 (9.13) |
| Blue | | | 4.17 (3.33) |
| Green | | | 7.08 (4.54) |
| Red | | | 2.75 (5.31) |
| White | | | 3 (3.74) |

*Note:* Values in parentheses are SD.
† In the case of the northern sector, only portions of the plants in shadow (i.e., unlit) are shown.
‡ In North sector only.

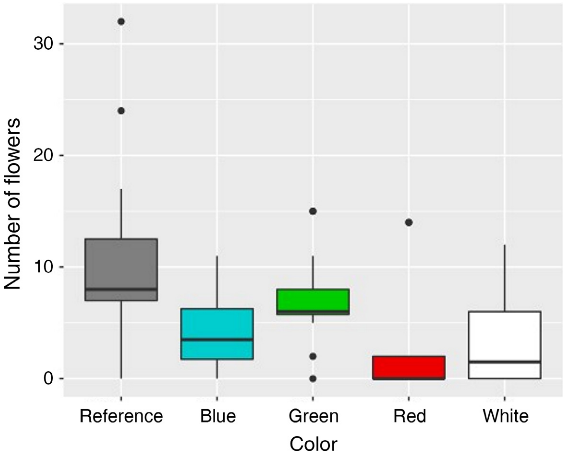

FIG. 6. Number of flowers produced by plants subjected to different light.

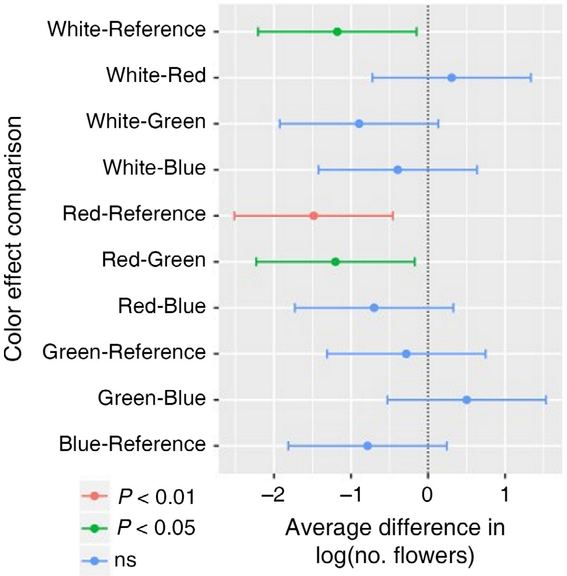

FIG. 7. Tukey test results.

sediments of the study area are fine carbonate sands and homogeneous. The granulometric distribution is unimodal, which confirms the aeolian character of these sediments. Also, Pérez-Chacón et al. (2007) analyzed the groundwater depth and salinity in both winter and summer at several points in this system. Their results show that the water table occurs at an average depth of about 51 cm with little to no spatial variation. In regard to salinity, the electrical conductivity thresholds in this area show the groundwater is slightly saline (between 5.7 and 7.2 per mS/cm) and again shows little spatial variation in the study area. In conclusion, according to the previous studies carried out in this area, it does not seem that there are other factors that may be influencing the smaller number of flowers produced by the *Traganum moquinii* specimens located in the northern sector of this system.

However, in order to confirm that there were no other factors that could be causing this alteration in natural conditions, a controlled experiment was conducted, the objective of which was to ascertain if under controlled conditions the exposure to extra artificial light altered also the reproductive potential for plant seeds of this species. In order to do this, the number of flowers produced by *Traganum moquinii* plants exposed only to natural light hours has been compared with the number of flowers produced by plants receiving extra exposure, in addition to a number of hours of artificial light with an intensity equivalent to that detected in the field. In addition, further research was conducted to verify whether some wavelengths of the visible spectrum affect the reproductive cycle of this species to a greater degree or not.

The results obtained are significant (Figs. 6 and 7), indicating that, in fact, exposure to extra artificial light alters the reproductive cycle of this species, reducing the production of flowers, and therefore, seed production. This decrease is different depending on the spectrum of light applied, so that the red and white lights produced greater alteration. This confirms for this species the conclusions by Borthwick and Hendricks (1960) that the more effective wavelengths to inhibit flowering are between 600 and 680 nm (orange-red). In short, it follows that the artificial lights of the promenade have an impact on the *Traganum moquinii* plants exposed to those lights, which results in a decreased production of flowers.

This study demonstrates the existence of a new form of impact that produced by artificial lighting, which has not been considered in these aeolian systems previously. This new impact adds to the significant impacts on the functioning of the aeolian dynamics and vegetation produced directly by the construction of a holiday resort in this system (Hernández-Calvento et al. 2014, Smith et al. 2017, Hernández-Cordero et al. 2018).

From a socioeconomic perspective, this study demonstrates how tourism directly alters the natural landscape, which, ironically, is one of the primary tourist attractions. Reducing the power of the spotlights, and relocating the lights to ground level, in order to illuminate the road and access points to the beach but not the wider natural environment, would be relatively easy and simple management options. Also, the establishment of lights with wavelengths less aggressive to plants would be advisable.

This work also potentially points to further scientific enquiry on the topic. For example, the light pollution could be inducing an anomalous growth in the specimens of *Traganum moquinii* more exposed to the artificial lights, which could have geomorphological implications. Since these plants have inhibited flowering, they could grow toward the lights. According to Raya

(2003), this would be due to the effect of phototropism, which implies a growth process towards a unilateral light by a redistribution of auxins. An abnormal plant growth means a reduction of space between neighboring plant specimens, altering the natural conditions of the normal foredune zone of these environments. In this case, the discrete nature and shape of nebkha dunes change to become larger eco-geomorphic units with semi-continuous surfaces covered by vegetation. The aeolian sedimentary dynamics would then be affected, since changes would then occur in the interactions between plants, nebkha development, and sediment transport pathways into the adjacent dune field (Cabrera-Vega et al. 2013*a*, Viera-Pérez 2015).

In addition, the impact of the artificial lighting may be even more intense due to the effect on insects. Light pollution, and in particular, the intensity and wavelengths of the lights can affect their phototoxic response (Wigglesworth 1953, Burkhardt 1964). Ultraviolet, blue and green lights are more attractive than yellow, red and infrared lights (Baker and Hieton 1952).

## Conclusion

To the authors' knowledge, this is the first study to demonstrate the effects of artificial lighting on wild plant species in a natural area, and also on the coastal plants of a foredune zone. Pollution from high-intensity artificial lights affects *Traganum moquinii* plants inducing at least a decrease in their potential for reproduction by seed. Long-term effects of lighting on these specimens induces an inhibition of flowering in the most exposed individual plants and parts of the plants. The artificial lighting also alters the spectrum of light received by the affected plants. Light between 600 and 700 nm primarily affects the reproductive cycle of the *Traganum moquinii* species. It is also possible that the growth of the plants and the insects that utilize the plants may also be affected.

From a local perspective, this phenomenon has long term negative consequences for the natural functioning of the Maspalomas dune system, and thus, for the socioeconomic environment as well, since this dunefield, which is heavily used as a tourist attraction, is being altered.

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