Spatial and temporal variation of light pollution in a highly structured nature reserve near Zürich

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Abstract

I examined the magnitude of light pollution at two spatial scales. On the regional scale, satellite data (VIIRS) was used to assess the exposure of nature reserves to light pollution across the canton of Zürich, Switzerland. To quantify the spatial and temporal variation of light pollution at the scale of an individual, strongly light-polluted nature reserve (Katzensee, canton Zürich), two methods were used: long-term monitoring using luxloggers and punctual monitoring using full-sphere photography along transects. Luxloggers allow high temporal resolution of measurements on a longer time-period but suffer from low sensitivity in dark conditions. Photography cannot be used for continuous monitoring but gives reliable measurements in all conditions that can be used to investigate small brightness differences at the local scale. Combined, those two methods can give comprehensive insights in an area.

At the cantonal level, satellite data shows that the 13% brightest reserves suffer from 50% of the total light pollution that occurs in nature reserves, while 68% of the nature reserves show low light pollution levels (<1nW as measured by VIIRS). Gravel pits were slightly brighter than dry meadows, wetlands, or bogs. Brightness of a reserve depends on proximity to settlement (light sources), whereby a small settlement within 1km can have the same light-pollution effect as a larger settlement at 5km.

The Katzensee belongs to the 5% most light-polluted nature reserves of the canton of Zürich. The luxloggers indicated that some nights without moon were clearly brighter than some nights with close-to-full moon, so the perception of the lunar cycle was found to be strongly disrupted. The main factor for such differences between nights is the weather, where clouds had an amplification factor of up to 10-12x. The photography results show that spatial variation (difference from one location to another) strongly differs depending on the weather. In cloudy conditions, the brightness was very high and constant over the whole area. In clear sky conditions, the whole area was homogeneously darker. In both those weather conditions, brightness is mostly determined by distant light sources (up to several km) and depends less on the close-by surroundings. On the contrary, in partially cloudy or foggy conditions, the presence of close-by (within 800m) light sources was more relevant for the average brightness at a given location, which became drastically brighter at closer distance to settlement.

Applied conservation management has suggested to provide dark-buffer zones around nature reserves in order to protect them from light pollution. For such a buffer, care should be given to two different brightness indicators: (1) the average brightness resulting from illumination within a 1km buffer, and (2) direct peaklights emissions such as from single streetlights or passing-by cars, which can have a considerate effect on luminous landscape as far as 500m away.

Introduction

Even if artificial lightning at night (ALAN) has been used by humans since millenaries, the problematic of light pollution was first thematised by the astronomical community in the 20th century (Cinzano, Falchi et al. (2000), Bazell, Riegel & Henbest in Huber (2007)). In recent decades, growing research has shown strong negative effects of ALAN on human health, human culture and ecology (Longcore and Rich 2004, Navara and Nelson 2007, Smith 2009, Stone 2018). In the field of conservation biology, ALAN is now widely recognized as an important threat for biodiversity (Holker, Wolter et al. 2010, Gaston, Bennie et al. 2013, Hölker, Jechow et al. 2014, Stone 2018, Hale and Arlettaz 2019).

Efforts to reduce and mitigate ALAN can take a wide diversity of forms, such as changing the type, light level and operating hours of streetlights, reducing light emissions of shop windows or advertisement, closing window blinds in the evening, turning off specific lights, etc. When strictly looking at the adverse effects of ALAN on the environment without any other considerations, one could just turn off all lights to solve the problem, which would not need any scientific basis. However, ALAN is very ambivalent and encompasses other issues than environmental protection, such as safety or enhanced entertainment possibilities after dark (Boyce 2019), which is reflected e.g. by legal requirements of public lightning. There is therefore a need for comprehensive lighting systems that enable optimum lighting where and when it is needed, but that can preserve darkness where it is of higher value (Stone 2018, Kretzer and Bolliger 2020).

On the one hand, mitigation can homogeneously take place at the level of a whole political unit, without prioritizing protecting important nature areas, for example as in the pioneer municipality Val-de-Ruz which globally reduced its lighting (Botteron 2018). On the other hand, mitigation of ALAN can also target specific areas that are important for nature conservation, at two different scales.

At the regional scale, mitigation can be done for example through the creation of dark sky reserves or by defining "black corridors" (Kolláth 2010). For such measures, there is a strong need for support from spatial research based on satellite and field data, that can show and explain the general light patterns at the regional scale. Many studies on ALAN have focused on satellite data to estimate the spatial extent of the problem, ranging from national or regional analysis (Bennie, Davies et al. 2014, Kyek 2019) to the creation of world atlases of artificial night sky brightness (Cinzano, Falchi et al. 2001, Falchi, Cinzano et al. 2016).

At the local scale, mitigation can take place in and around areas that have previously been defined as important for nature conservation. A typical example for such areas is nature reserves, that are often but into place to protect specific endangered habitats or species, and thus merit extra protection, including from adverse effects of ALAN. Attempts to analyse the extent of ALAN in those valuable nature areas has been done in Switzerland by Hale and Arlettaz (2019) or Kyek (2019), using satellite data. However, local implications for regions categorized as strongly lit based on satellite images remain unclear as local landscape composition (e.g., forest vs. agriculture or settlement area) and configuration (spatial arrangement of e.g., settlement, relief) may drive the local-scale distribution of light sources.

Therefore, research on the distribution of ALAN in the environment at the local scale is important, particularly for nature reserves: How does the effect of a given streetlight decrease with distance? How does the presence of high vegetation affect the brightness patterns? Is blending off a light source enough to reduce the total imissions in the field, or is its contribution to sky glow too strong in comparison? What is the brightening effect of cars passing by? How do different light spectra spread in the environment? How do all those effects vary with different weather conditions?

Research on those questions is not yet complete, and precise explicit insights are often missing. However, for generalizing these local mitigations over a broader area, it is crucial for policymakers such as the cantonal authorities that those questions be scientifically treated to allow for concise, useful and well-accepted policies. This is the case for example for representatives of the canton of Zürich, who acknowledge the significant impact of ALAN on biodiversity and want to reduce the impacts on nature reserves by adapting new specific policies (Weber 2020).

This study aims to conduct a spatial analysis of light pollution both at the cantonal scale and at the local scale in a specific area. Specifically, I focused on the nature reserves (hereinafter NSO, *Naturschutzobjekt*) of the canton of Zürich, which contains the most light-polluted NSO of Switzerland after Basel Stadt (Hale and Arlettaz 2019).

In a first part, I analysed satellite data over the whole canton of Zürich to quantify the extent of ALAN intensities in nature reserves of Zürich. This approach allows to get some good insights about the general trends, to assess where it is particularly bright, and why. But how bright is bright? What can be considered as too bright? These are very tricky questions for the practice. Therefore, a second part was consecrated to an in-depth analysis of the ALAN patterns at one of the brightest and biggest nature reserves of the canton of Zürich, the Katzensee, which can serve as a reference for other light-polluted nature reserves and give useful insights for further research projects. In this part I combined field data from standard luxloggers and from full-sphere photography to assess the temporal and spatial variations of light pollution at the small-scale.

The overall goals of this study are to (1) give an overview of light pollution across the canton of Zürich, (2) quantify the distribution of light in a selected highly light-polluted nature reserve and gain insights about the local spatial and temporal variation of light pollution, (3) test and develop a methodology for measurements of light at night, and (4) derive recommendations for conservation practitioners.

Part 1: ALAN exposure in nature reserves in the canton of Zürich

1.1 Introduction

In the highly light-polluted canton of Zürich, I aim to quantify the exposure of single nature reserves (NSO) to artificial light at night (ALAN) and explain the patterns observed. I used satellite data to investigate how bright are the NSO at night. How many NSO have high light pollution levels? I hypothesized that high pollution is closely correlated with the presence of settlement nearby, which we expect to have different effects depending on the scale of proximity and size of settlement. In a general way, the most impacted reserves should be located close to big urban centres, and the presence of streetlights or buildings in close vicinity should also have a positive impact. Following the results of Kyek (2019) and Hale and Arlettaz (2019) for Switzerland, I expected wetlands to be more impacted than dry habitats. Using the gained insights, I tried to define what impact reduction strategies might be more sensible to implement for the practice.

1.2 Material and methods

Study area

Zürich is one of the most light-polluted areas in Switzerland (Fig. 1, Hale and Arlettaz (2019)). It is the 7th biggest swiss canton, with a total area of 173 km^2. Agriculture has the main land share with 40%, while 30% of the territory is forest, 23% settled area and 7% unproductive area (Ferrer, Lo Russo et al. 2020). Outline of the canton is drawn in Fig. 1 and Fig. 2.

Data

I used data about the NSO, streetlights, building footprints, habitant density, as well as satellite data for light pollution.

NSO

I conveyed the analysis only with NSO of regional or national importance, to simplify and homogenize the dataset. For the NSO of national importance, I extracted data from the Zürich cantonal geodataset n°320 *Überkommunale Naturschutzobjekte und schützenswerte Gebiete*[1]. From all NSO marked as of national importance, I selected only those that were also monitored in the cantonal inventory of nature and landscape protected areas from 1980 (cantonal geodataset n°127 *Inventar der Natur- und Landschaftsschutzgebiete von überkommunaler Bedeutung*, see first footnote for source of all cantonal geodatasets). This was done in order to be able to transfer feature information between the datasets, for the sake of data consistency. This procedure took away from my analysis 60 NSO of national importance, most of them being dry sites or amphibian spawn areas. For the NSO of regional importance, I used the data from the cantonal geodataset n°165 *Schutzverordnungen über Natur- und Landschaftsschutzgebiete von überkommunaler (kt./reg.) Bedeutung (SVO)*, which contains all nature reserves of regional importance that are legally binding for the authorities. I selected from the *SVO_ZONEN_F* layer all areas classified as “protected nature area” and “protected nature surrounding area”, apart from those that were already covered by the NSO of national importance, to avoid duplicons. I then combined both datasets into one. All adjacent areas or areas that belonged to the same object were consequently merged and manually checked for errors.

Settlement proximity

Built-up area: I used a raster with building footprint information from the swisstopo swissTLM3D © 2019[2]. The polygon data of the footprints was transformed into a raster featuring the amount of built-up per 12.5x12.5m cell.

Population density: I used data from the population census STATPOP2016 from the BFS GEOSTAT[3], which gives the number of inhabitants per 100x100m cell.

Streetlights: The cantonal geodataset n°124 *Beleuchtungskataster Staatsstrassen (ohne Städte Zürich und Winterthur)* was used to retrieve individual streetlight positions along cantonal streets. For NSO that were closer to the cities of Zürich or Winterthur than to the next streetlight, NA was attributed, since those two cities were not covered by the dataset.

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[1] All the used geodatasets from the canton of Zürich and corresponding metadata is publicly available under: https://are.zh.ch/internet/baudirektion/are/de/geoinformation/geodaten_uebersicht/geodatenshop.html (retrieved 23.03.2020)

[2] https://shop.swisstopo.admin.ch/en/products/landscape/tlm3D (retrieved 30.04.2020)

[3] https://www.bfs.admin.ch/bfs/en/home/services/geostat/swiss-federal-statistics-geodata/population-buildings-dwellings-persons/population-housholds-from-2010.html (retrieved 30.04.2020)

Light pollution

For the light pollution satellite data, I used the VIIRS-DNB dataset from the Earth Observation Group of the Payne Institute for Public Policy (Elvidge, Baugh et al. 2017)[4], which is better than the until now commonly used DMSP dataset (Elvidge, Baugh et al. 2013). This satellite dataset contains monthly composites of upward radiance values (i.g. amount of light that is emitted from the ground in direction of space, see more about radiometry and photometry in Appendix A) at night (daily data collection at around 01h30, see Kyba, Garz et al. (2015)) at a scale of 15 arcsec (in Zürich, this corresponds to about 313x463m). Using as reference the September composites to avoid stray-light contamination from summer and snow and temporary lightnings in the winter (Hale and Arlettaz 2019), I took the average values for 2016, 2018 and 2019 (year 2017 was slightly off grid, therefore it was not used in the calculations), and used those values in the following analysis.

Analysis

All manipulations with spatial data was executed with ArcMap 10.6.1 from ESRI and statistical analysis with R 3.5.2. I computed the averaged upward radiance for all selected NSO in Zürich, averaging all VIIRS pixel values within a buffer of 300m around and within each NSO. To model settlement proximity, I computed for each NSO the population density within a buffer of 1 and 5 km around the NSO area, average distance to next building, distance to next cantonal street's streetlight from NSO perimeter, and % of built-up area within a 1km-buffer around and within the NSO area. Those metrics were chosen because they all correlate with light emissions within an area and represent effects at different spatial scales. Even though they can give useful insights in a specific area, metrics that give more detailed information about an NSO, such as shape index or % of forest cover, were not included. This is because I assumed that they are irrelevant to the upward radiance as measured by a satellite. Generalized linear models (GLM) without interactions (to avoid overfitting and allow easier interpretation) were used to model the radiance per NSO from those metrics as well as from the relevance (cantonal/regional) and size of NSO. The models were all calibrated using the glm function from the stats R-package, with a Gamma-family with identity-link, which was chosen to best match the non-gaussian distribution curve from NSO radiance. Firstly, for each explaining variable, either the non-transformed, the log-transformed or the squared data was chosen, based on smallest residual deviance. AIC criterion was then used to select the best model among all metric combinations, using the stepAIC function from the glmulti 1.0.7.1 R-package[5]. The vif function from the car 3.0-6 package[6] was used to compute vif values for the models to assess multicollinearity among variables. Spearman and Kendal correlations were also computed between the variables of the final model.

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[4] For more information and data processing papers, see https://payneinstitute.mines.edu/eog/nighttime-lights/ (retrieved 24.03.2020)

[5] https://www.rdocumentation.org/packages/glmulti/versions/1.0.7.1 (retrieved 24.03.2020)

[6] https://www.rdocumentation.org/packages/car/versions/3.0-6 (retrieved 01.05.2020)

1.3 Results

Over the whole canton, a total of 683 NSO was selected and categorized into their main ecological type: 163 dry sites (mostly grassland, incl. 6 amphibian spawn areas of national importance), 327 wetlands (incl. 35 amphibian spawn areas and 11 flood plains of national importance), 166 bogs (incl. 31 amphibian spawn areas of national importance) and 27 gravel pits (incl. 15 amphibian spawn areas of national importance). Half of the NSO are of regional importance, half of them of national importance (see map in Appendix B).

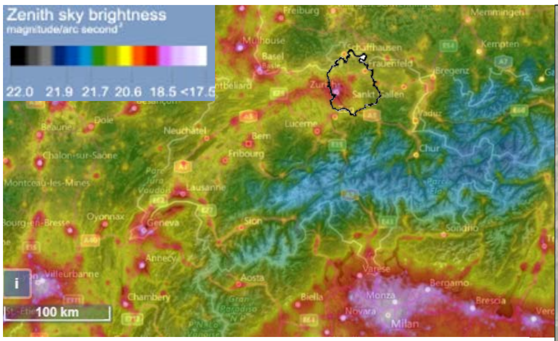

Figure 1: Light pollution in and around Switzerland. Milano is very visible in the South, as well as Lyon in the West. In Switzerland, Genève and Zürich (black outline) are the two biggest light pollution centres. The Swiss Plateau, in the axis between those two cities, is also very impacted. Map from Falchi, Cinzano et al. (2016)

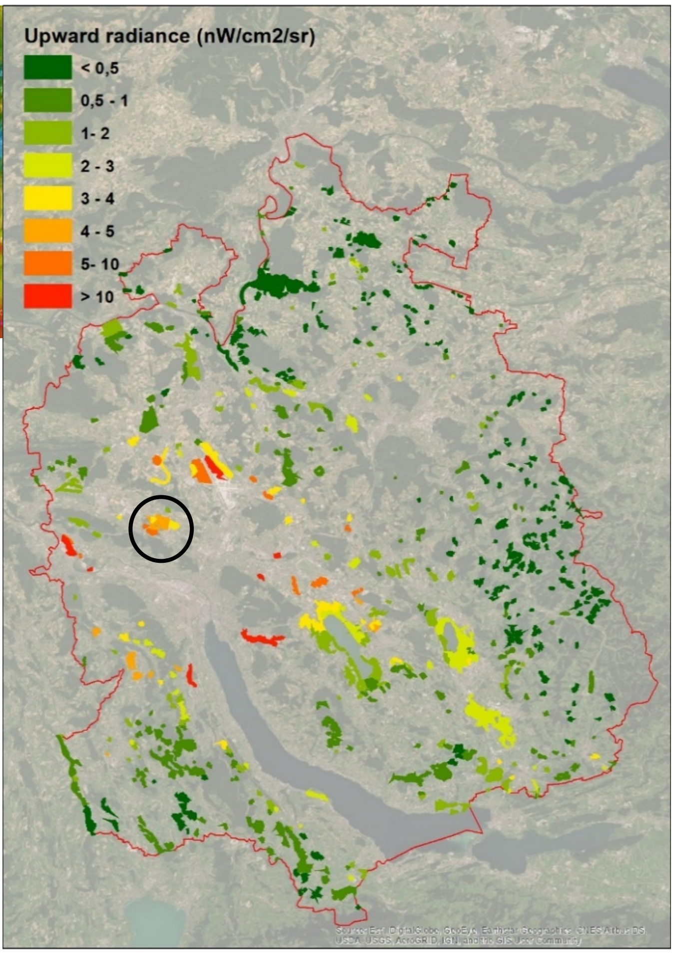

Figure 2: Selected nature reserves (NSO) of the Canton of Zürich. The colour depicts the mean radiance at each site from the VIIRS satellite-data.

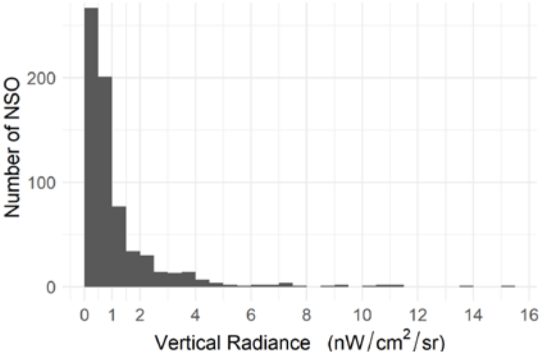

Figure 3: Distribution of NSO radiance in the canton of Zürich. The y-axis represents the number of NSO per 0.5 nW bin.

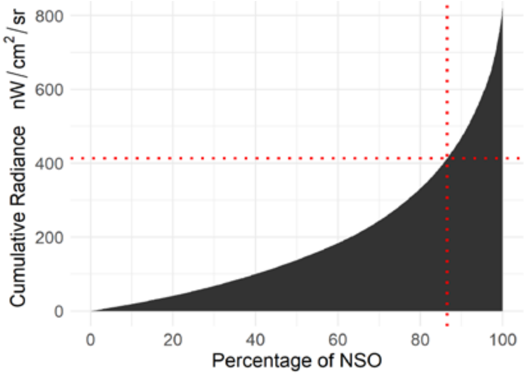

Figure 4: Cumulative sum of radiance of all NSO as derived from VIIRS. This graph shows that 50% of the total upward light emissions around NSO of the canton of Zürich are concentrated around the 13% brightest NSO.

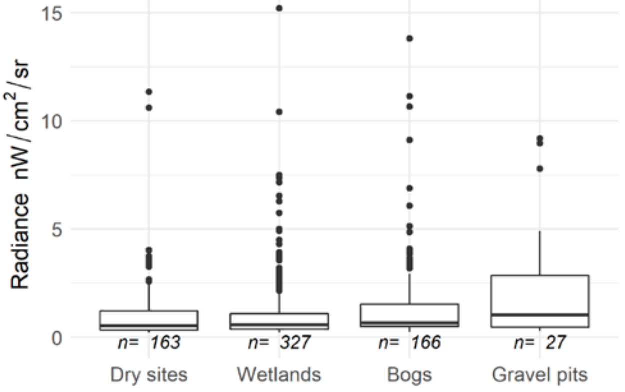

Figure 5: Radiance per type of NSO. As around only 30% of the dry sites, wetlands and bogs have radiances >1 nW, 50% of the gravel pits have radiances >1 nW.

A map of the distribution of nocturnal sky brightness shows that the area of Zürich is among the most impacted regions of Switzerland (Fig. 1, Falchi, Cinzano et al. (2016)). Brightness values range from 21 to less than 19 mag/arcsec^2. Fig. 2 depicts the mean radiance of all selected NSO in the canton of Zürich. Only a very small fraction shows "high" levels of radiance, with 68% of the NSO below 1 nW and 85% below 2 nW (Fig. 3). As shown in Fig. 4, 13% of the brightest NSO account for 50% of the total radiance. Almost all the most polluted NSO are concentrated around the city of Zürich.

Among NSO, all ecological types are similarly exposed to light pollution (Fig. 5). The only exception is for gravel pits, with a median radiance of >1nW, while the median for dry sites and wetlands were ~0.55 nW, and 0.67 nW for bogs. Gravel pits are therefore the most impacted NSO, but interestingly some outliers from the dry sites, wetlands and bogs are even brighter than the brightest gravel pits.

Using the selected transformed data (no transformation vs log or squared) for each explaining variable, all fitted models for predicting radiance at a given NSO from the landscape metrics were compared based on the AIC criteria. The last step of the selection procedure is shown in Appendix C to give an overview of the AIC values for different models. The chosen model with the lowest AIC is explained in following Fig. 6:

Radiance ~ $PopDens1000^2$ + $PopDens5000^2$ + log(DistLamp) + $BuiltUp^2$

PopDens1000: Population density within the next 1km (n/km2)
PopDens5000: Population density within the next 5 km (n/km2)
DistLamp: Distance to next streetlight on a cantonal street (m)
BuiltUp: Built-up area within the next 1km (%)

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                 Estimate Std. Error t value Pr(>|t|)    
(Intercept)      4.862e-01  7.608e-02   6.391 3.14e-10 ***
I(PopDens1000^2) 3.049e-06  4.128e-07   7.385 4.71e-13 ***
I(PopDens5000^2) 3.719e-06  3.048e-07  12.201  < 2e-16 ***
log(DistLamp)   -4.111e-02  1.099e-02  -3.741    2e-04 ***
I(BuiltUp^2)     4.323e-03  5.178e-04   8.348 4.18e-16 ***
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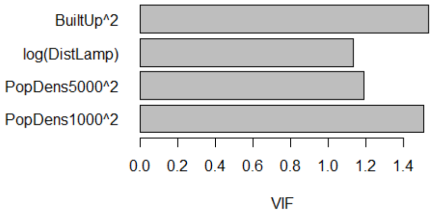

Figure 6: Chosen model for predicting radiance as derived from VIIRS at NSOs of the canton of Zürich.

This model has a R^2 of 0.83 and is fit with four variables for a total number of observations of 654. All variables are highly significant. The squared population densities within 1 and 5 km do not show a multicollinearity problem, as shown by the VIF values (Flom 1999). BuiltUp is more closely correlated to PopDens1000 (Kendall's τ: 0.67, Spearman's r_S: 0.86), but not in a problematic way, as shown again by the small VIF-value of 1.5. Correlation matrix between the variables is given in Appendix C for further information. The squared Population density within 1 and 5 km have a very similar highly significant positive effect, and so does built-up area. These three metrics have similar behaviours, such as the one for built-up area illustrated in Fig. 7, and tend to increase exponentially with increasing size of settlement. On the same line, radiance diminishes significantly with larger

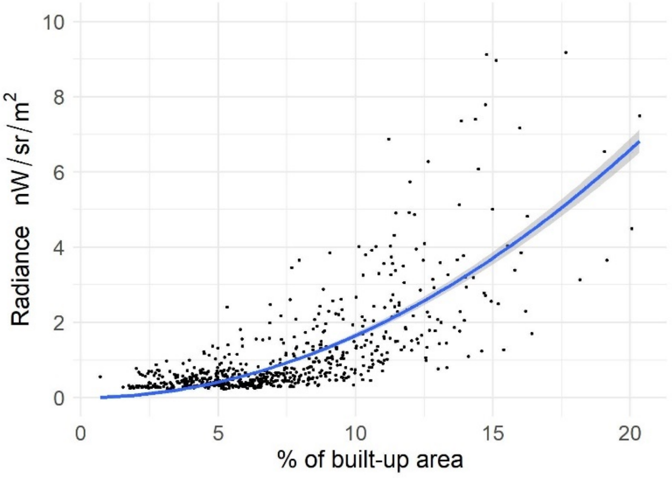

Figure 7: Effect of built-up within 1km of a nature reserve on the measured radiance at the NSO. The blue line represents the linear regression line between the measured radiance and the squared % of built-up area. R2 is 0.69.

distance to the next cantonal street's streetlight. Supplementary figures for the effect of distance to streetlight and population densities can be found in Appendix D.

1.4 Discussion

Europe is regarded as one of the most light-polluted regions of the world (Falchi, Cinzano et al. 2016, Falchi, Furgoni et al. 2019), and Switzerland's Plateau is not an exception. There is a general consent that nature areas are subject to high light pollution levels. My analysis of the VIIRS dataset showed that those NSO that are within close distance to an important settlement can indeed have very high upwards radiances. However, apart from those extreme cases, it is difficult to estimate what radiances should be considered as too high, since there are no explicit VIIRS-value thresholds in the literature. Brightness values of 2nW are considered typical for parts "of a small village" by Hale and Arlettaz (2019). As an example, using this value as the low pollution threshold, 85% of all NSO in the canton should not be highly impacted by light pollution. Using a more conservative threshold of 1nW, still 68% of the NSO should be considered as "lowly polluted", which is quite satisfactory. This doesn't mean that no care should be given to preserving those areas. On the contrary, NSO with low levels of light pollution might provide habitats of higher quality for biodiversity and should be preserved with extra care. Those more pristine areas might be particularly sensitive to single local light sources such as a very bright lamp from a farm, whose relative impact could be very high, but remain undetected by satellite data. Therefore, extra monitoring could be put into place to detect small-scale lightning issues and avoid "ruining" an else little polluted area (see example in Appendix E, Figs. 22-23). On the other hand, NSO with high pollution levels should draw the attention to the general light emissions in an area and could probably be significantly improved by reducing overall emission sources.

The most impacted NSO are gravel pits. Sadly, those are often considered as very valuable changing habitats for different r-type plant and insect species or amphibians and are often used as ecological compensation areas. Therefore, close attention to light pollution should be paid during the case-by-case process of gravel pits revitalisation or ecological valuation. Other habitats were not found to have different light pollution levels. Especially wetlands, which were expected to be more polluted (see Kyek (2019) or Hale and Arlettaz (2019), were not brighter. This can be due to the specificities of the canton of Zürich (in comparison to Switzerland), but also to the fact that not only NSO of national importance have been used as in both studies, but also a lot of small wetlands of regional importance, many of which are in rural areas, and therefore possibly less polluted.

My model results are not surprising, since all metrics used were thought to correlate with total light emissions in an area (the more people the more light, the more buildings the more light, and the closer the streetlight the more light). Those metrics could all serve as proxy for an "index of proximity of settlement", and it would be interesting to try combining them to create such an index, to facilitate comparison of NSO. Such an index could also serve across different research topics to compare areas. Very interestingly, it is a combination of Population densities within two different buffers (1 and 5 km) which provides the best model fit. Since those two metrics have very similar estimates, this shows that the effect of a settlement needs to be regarded at different spatial scales. A small settlement within very close distance can have a similar impact as a bigger one further away. This is conceptually consistent with findings from Kocifaj and Lamphar (2014) with their skyglow modelling. Population density within 1 km has a relatively high correlation with the built-up area within a buffer of 1km, which makes sense, even if it might reduce model quality. However, the inclusion of built-up area in the model considerably reduced the AIC, and R^2 was slightly improved. Moreover, including the latter allows the integration of areas where nobody or few people live, such as farms or industrial areas, but which can still have high light emissions, which is a conceptional improvement of the model. Finally, built-up area is more easily observable and controllable in the practice and should therefore be included. Another interesting result is that the effect of those metrics is not linear. Indeed, the effect of distance to the next streetlight is stronger at close range and metrics for population densities and built-up area are all squared in the model. This suggests that a certain threshold could be found, under which the effect of population density and built-up area stays relatively small. Those thresholds could be relevant for the practice. Taking the example of built-up area (see Fig. 7), one imaginable way to mitigate ALAN exposure in NSOs could be to allow constructions in construction zones within a 1km buffer around a NSO, but with a maximum of 5% of built-up area, in order to limit light emissions and therefore exposure to ALAN. Indeed, higher than this threshold of 5%, the effect of any supplementary building would be bigger and bigger. The same applies for population densities, which are however more difficult to control for in the practice.

Part 2: Spatial and temporal variation of exposure to ALAN in the Katzensee nature reserve, canton Zürich

2.1 Introduction

A major drawback of using satellite data to quantify artificial light at night (ALAN) is that only upwardly directed radiance (light emitted from ground towards zenith) under clear sky conditions are measured. However, a given upward radiance under clear sky doesn't necessarily represent the brightness relevant for impact assessments on ground due to light scattering, topography, vegetation structure or polarization on water surfaces (Kyba, Garz et al. 2015). For example, a forest clearing in a bright area might be darker than expected due to the protective effect of the forest. Alternately, a location close to a lake might be brighter than expected due to reflections of the light on the water surface (Lynch, Dearborn et al. 2011). Moreover, ALAN impact on the environment may vary depending on weather conditions (Kocifaj and Lamphar (2014), Jechow, Kollath et al. (2017), Jechow and Holker (2019) & Kyba, Tong et al. (2015)). Indeed, in strongly light polluted areas, light pollution levels can be up to 18 times higher in overcast conditions than with a clear sky (Kyba, Tong et al. 2015). In those areas, the actual brightness on sites with special weather such as cloudy or foggy conditions would be strongly underestimated while only using satellite data as estimator. While this is probably less an issue in darker rural areas (even if there are clouds, there is very little light to be reflected down anyway), this is more problematic in bright areas, where the light levels at given times could be a lot higher than expected.

Therefore, does a nature reserve (NSO) classified as heavily light polluted based on satellite data also qualify as heavily light polluted given light impact measurements on the ground? Also, what is the magnitude of spatial and temporal variation of light pollution at a given NSO? I conducted measurements in one of the most emblematic suburban nature reserves of Zürich, the Katzensee (FNS 2008), which proved to be one of the brightest big NSO of Zürich (4nW, >50 ha), second only to the Altläufe Glatt close to Zürich airport. To assess spatial and temporal variation in ALAN levels and distribution, I used two complementary methods: temporally punctual all-sphere photography at a high spatial resolution, and temporally continuous light monitoring using luxloggers. I aimed to define use and limitations of both methods, as well as to highlight possible synergies.

From a spatial perspective, I tested the contributing effect of proximity to settlements on light pollution within the NSO at different scales and qualitatively assessed how this effect varies under three frequently encountered weather conditions: cloudy, foggy and clear sky. Since the Katzensee is a suburban highly polluted area, I expected cloudy and foggy nights to be a lot brighter than clear sky nights. From the temporal perspective, I expected an average decrease of light pollution over the course of the night and modelled how big the intra-nocturnal changes are. The inter-nocturnal differences (between nights) should be even higher, mostly depending on weather conditions and moon brightness. I expected the effect of moon to be sensitively bigger than the effect of ALAN, at least under close-to-full moon conditions.

For both temporal and spatial variation, I wanted to investigate the effect of “peaklights”, which I defined as punctual light sources, isolated either spatially (e.g. a single lamp) or temporally (e.g. a passing-by car). By comparing different measurements, I tested the hypothesis that those lights can have a big influence on total brightness.

Lastly, I give recommendations for further research and applied conservation management based on my findings.

2.2 Methods

Study site

All measurements were conducted in and around the nature reserve of Katzensee in the communes of Zürich, Regensdorf and Rümlang (see Fig. 2 for location). The Katzensee is a 90 ha highly structured nature reserve, which contains forested areas, two ponds, wetlands, meadows, a fruit orchard and a lot of landscape structures such as hedges, isolated trees and bushes (Fig. 8). The actual nature reserve area of Katzensee is surrounded by additional zones of landscape protection, so the total protected area amounts to 413 ha. The whole area is flat, even though some very small relief locally changes the horizon visibility.

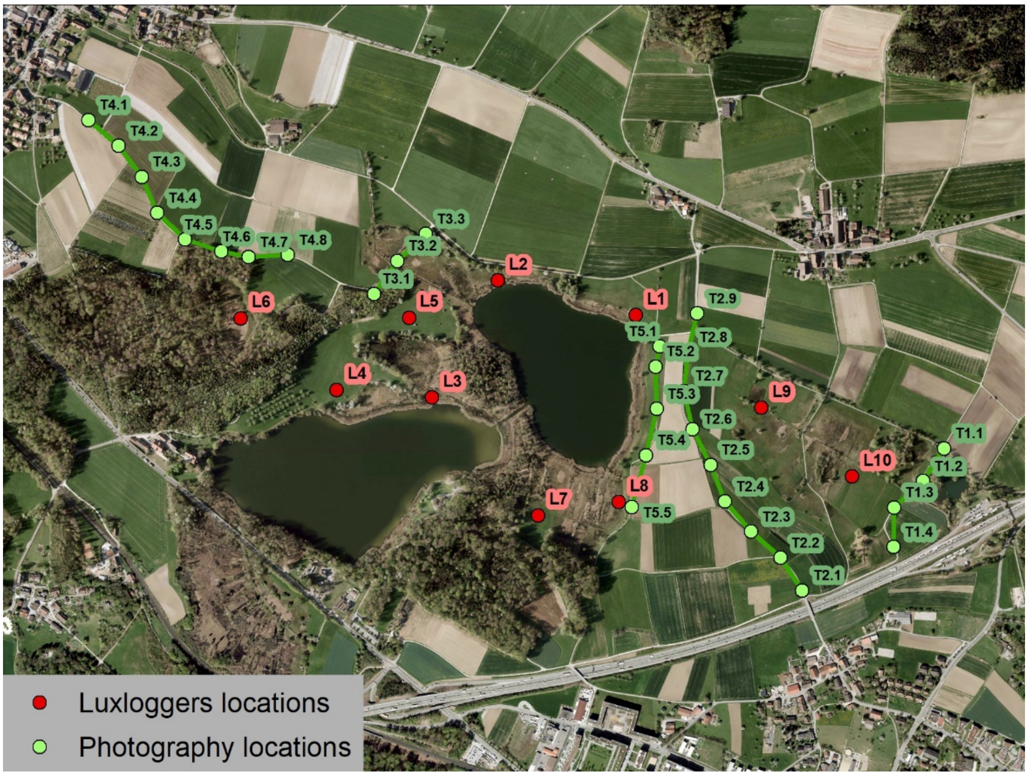

Figure 8: Experimental set-up at Katzensee. The red L1-L10 represent the long-term light monitoring locations, and the green T’s represent the photography transects. The location of the Katzensee in Switzerland can be seen in Fig. 2. Basemap: Zürich cantonal dataset n°394: Orthofoto Frühjahr RGB 2015/16O

Luxloggers

I used 20 MSR® MSR145WD luxloggers to measure illuminance temporally continuously (incoming luminous flux, see Appendix A for photometry indications). The devices were calibrated by the manufacturer and measure illuminance ranging from 0.045 to 65’000 lx with an optical response matching the spectral response of the human eye.

A test phase was conducted at two locations (L5 and L7, Fig. 8) to determine optimal use of the luxloggers. The loggers were mounted on commercial sticks (derived from a garden centre) at 160 cm above ground. The luxloggers were mounted to the sticks using tape and cable ties (Fig. 9). Since the loggers measure light only from a given direction, on each of the two locations, ten loggers were mounted: two measuring light from the horizon in the North, two from the horizon in the South, two from the horizon in the West, two from the horizon in the East and two from the direction of Zenith. All loggers measured illuminance every minute between the 20th and 23rd of December 2019. Data was manually retrieved on the 23rd of December after the measurement period and was then analysed to find the optimal set-up (number and direction of luxloggers per location) for the long-term monitoring, using Spearman correlations between each logger or group of loggers and the average values for of all loggers.

In a second phase, a combination of two loggers pointed toward Zenith was used at each location, each logger mounted on an individual flower stick at around ~170cm (Fig. 9). Per location, while both loggers pointed toward Zenith, one was oriented to the North and one to the South, to account for possible differences in directionality for the measurements (see illustration in Fig. 9 lower picture). The loggers were dispatched at 10 locations within the Katzensee area, at least 200m from each other (L1-L10, Fig. 8). All locations were within the reserve and cover most of the different open-land zones. The specific locations were chosen in order to be least visible or accessible from walking paths, and as far away as possible from the surrounding high vegetation, in order to maximize sky visibility. Continuous measurement (1 per minute) was conducted between the 24th of December 2019 until the 7th of February 2020. The data was manually retrieved on 7th of February 2020 and

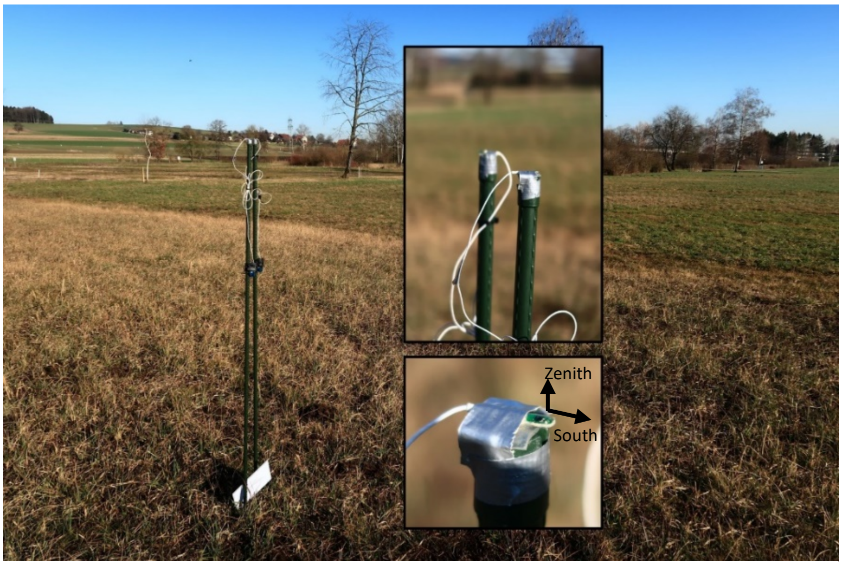

Figure 9: Setup for the monitoring with luxloggers at L10. Lower photograph shows one of the 2 loggers pointed toward Zenith and oriented to the South. The other logger is rotated 180° to the North.

then assembled together with information from single nights (e.g. moon, sun and cloud coverage information[7]).

Full-sphere photography

The basic set-up per location and time was to take two photographs pointed at the horizon, in two different directions (North and South). This allows to obtain images that cover 88% of the full sphere solid angle, with two "circular holes" at the Zenith and towards earth of respectively 6% of the full sphere angle each. The Samyang 8mm f/3.5 CS II was used, mounted on a Canon EOS 5D Mark II. While aperture remained constant at 3.5, ISO and shutterspeed was each time set to minimize local oversaturation without getting too underexposed images. This was optimized by trial and error. At locations and times that showed a lot of contrast in the image (e.g. close bright lamp or clouds), sometimes several images were shot to check for sensitivity of the results to settings. Images were taken in RAW format with 20 megapixels.

Images were taken at each of the Luxloggers locations (L1-L10, Fig. 8) in three different nights. Care was given not to illuminate the loggers. The three nights were chosen to cover a wide range of brightness conditions: one night with high clouds and no moon, one night with clear sky but half-moon, and one night with little clouds and no moon. I also set up five transects along walking paths to investigate the local variation of light intensities along gradients representing: distance to settlement, distance to light source, direct lightning, shadow from trees or bushes and relief variation. The specific transects were chosen to represent only one or two of those gradients at a time, in order to be able to isolate the effects. Locations were set on the transects around every 100 meters (Fig. 8, green lines and points). Each photograph series consists of 2 images at all of the locations of a given transect, taken as fast as possible to minimize changing light conditions from moving clouds. When the light conditions changed too much during a series (this was usually not the case in a night without wind), the series was taken out of the analysis. Series were done repeatedly, at different times of night and with different weather conditions at all transects. They were consequently classified in 3 categories by observation in the field: 100% cloud cover, cloudy-foggy, and clear sky. If none of those categories was applicable or if classification was ambiguous, NA was attributed to the series. All were done while moon was at least under 10° below the horizon, to avoid stray light effects.

Additional pictures were taken at T1.1 (see Fig. 8, in the very East). This location was chosen because of the relatively dark conditions and the presence ~550m away of a street with regularly passing-by cars and several streetlights. Pictures were taken towards the street (North) at regular intervals, trying to get images while cars passed by, and right before and after the streetlights got turned on, at 5 am. To assess the influence of weather on brightness variation, the measurements were repeated during a night with high clouds and a night with foggy conditions.

Photography processing

Analysis of the photographs follow the approach described by Hiscocks (2014). The pictures were all analysed using the open-source collection of GNU Octave routines DiCaLum from Kolláth and Dömény (2017), using the calibration data from Zoltan Kolláth. The raw files were converted to matrices of spectral radiance of the r, g, b bands (see Appendix A for more information to radiometry). From each raw picture, false-colors images reflecting r,g,b radiance as well as RGB-

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[7] Moon and sun information: https://www.timeanddate.com/moon/switzerland/zurich (retrieved 25.03.2020)
Cloud coverage information: https://www.worldweatheronline.com/zurich-weather-history/ch.aspx (retrieved 25.03.2020)

images on a standardized scale were extracted. I computed the mean and maximum radiance of the green bands, the former beeing then used as proxy-values for brightness in further analysis.

Landscape metrics

All investigated locations (long-term locations and photography transect locations) were characterized using landscape metrics. All were computed with ArcMap 10.6.1 from ESRI, using data for building footprint and population census (for data source and format, see Methods in Part 1), as well as a Canopy Height Model (CHM) and Digital Elevation Model (DEM) issued from LiDAR data (cantonal geodataset n°298 *Digitales Terrainmodell (DTM)* and n°299 *Digitales Oberflächenmodell (DOM)*[8]*).* For each location, I computed the population density (n/km^2) and % of built-up area within buffers of 250m, 500m, 750m, 1000m, 1250m and 1500m, distance to next building (m) and sky visibility (%), using the Skyline Graph function from the ArcMap spatial analyst extension. Those were compared with the photography results.

Measurements analysis

Temporal variation: Moon light and ALAN can be considered as incoherent light sources, and thus mostly have an additive effect when combined. This allows to correct the measured illuminance for the effect of moon using a simple regression line (LuxMeasurement = a + b*MoonLuminance), where MoonLuminance is the percentage of the maximum luminance from the moon. The fitted effect of moon was subsequently substracted from all measurement with moon (CorrectedLuxMeasurement = LuxMeasurement – b*MoonLuminance). This corrected data was used with the ts and decompose function from the stats R-package (R 2.5.3) to analyse the evolution of illuminance over the course of a night (intra-nocturnal variation, periodicity of data), as well as the general differences between nights (inter-nocturnal variation, trend of data), independently from the apparently random measurement variations.

I compared photographs at the luxlogger locations and the measurements from the loggers (average from 5 min before to 5 min after photograph), to establish the illuminance range at which the loggers give consistent values.

Spatial variation: The photography transects results were visually assessed and qualitatively compared using the computed landscape metrics and assigned weather classification.

2.3 Results

Temporal variation

Fig. 10 shows the measured illuminance from the luxloggers per night and location (see map on Fig. 8), one location being represented by the mean illuminance value between the 2 loggers at each location. The dots show the course of the moon over the month (% of moon surface illuminated).

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[8] All the used geodatasets from the canton of Zürich and corresponding metadata is publicly available under: https://are.zh.ch/internet/baudirektion/are/de/geoinformation/geodaten_uebersicht/geodatenshop.html (retrieved 23.03.2020)

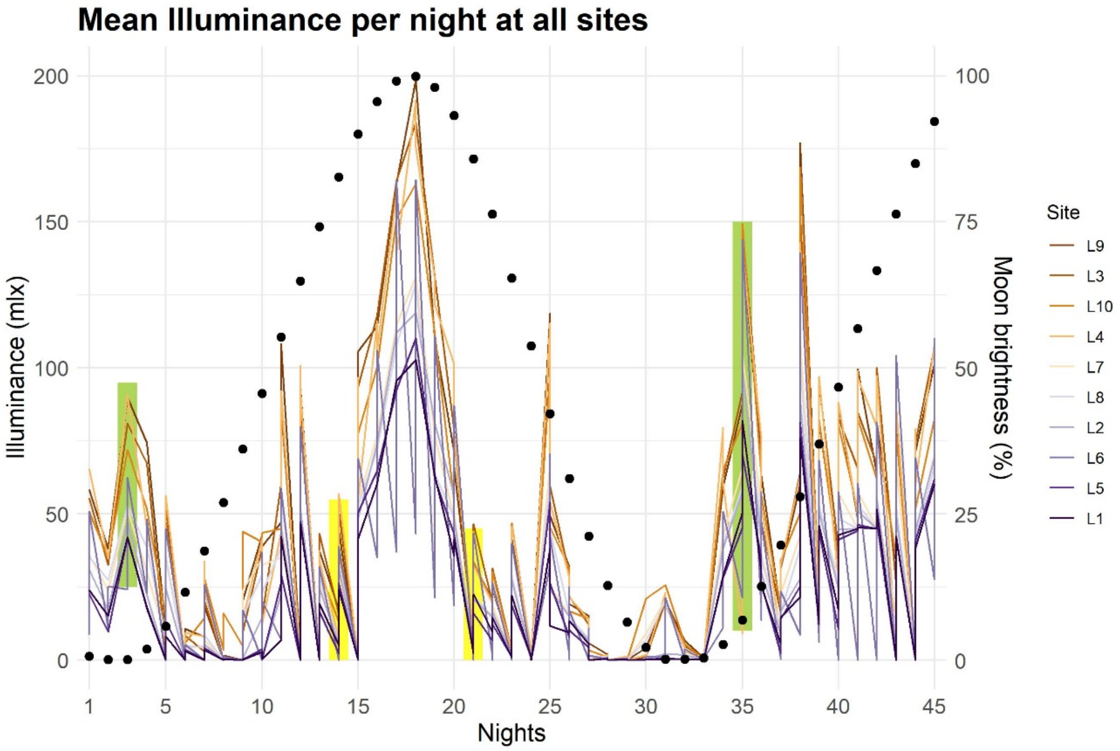

Figure 10: Measurements from the luxloggers. Each coloured line represents the mean Illuminance at one location (L1-L10, see Fig. 8), averaged per night. The black dots represent the course of the moon (% of area visible per night). The green highlighting points out nights without moon but bright, the yellow one nights with moon but dark.

When amplifying the graph, one observes that the lines don't cross a lot, so all locations follow the same patterns of variation. That means that the "brighter" locations during bright nights still are the brighter locations in darker nights. This could not be shown during a lot of the darkest nights, in which a lot of null values are measured. Also, it is clear that nights without moon can have illuminance values a lot higher than the darkest nights with full moon (for example compare bright nights without moon highlighted in green with dark nights with moon in yellow). Specifically, 15% of the darkest measurements with full moon (>90% brightness) are darker than the 15% brightest measurements without moon. The several peaks and strong variations between nights is investigated in the following paragraphs.

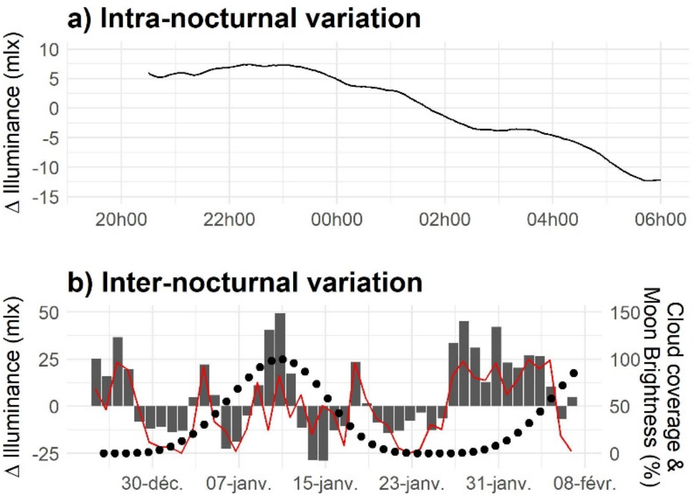

Figure 11: Modelling of illuminance variation from the loggers, using a moving-window approach with the R-stats function ts. (a) shows the predicted intra-nocturnal variation, which is the typical (average) course of illuminance over a night. (b) shows inter-nocturnal variation of illuminance, which is the difference of illuminance between single nights. The data was corrected for moon influence. The black dots represent the moon brightness per night, and the red line is the mean cloud coverage per night.

The linear regression between Illuminance and moon brightness shows that the measured illuminance increases by 0.7 mlx per % of moon maximum luminance. This makes a modelled difference of 70 mlx between full moon and no moon.

Fig. 11a shows the averaged temporal variation of illuminance over the course of a typical night (without moon). Illumination seems constant until midnight, but shows a clear decrease over the the rest of the night. There is a difference of around 20 mlx between the peaks. For a bright night of 100 mlx, this corresponds to an approximate decrease of 3% per hour after 23h. These values are overall averages. It is important to note that original data contains a lot of noise, with differences within a single night ranging from 10 mlx to 200 mlx (for full moon nights), which exceeds by far the average variation (Appendix F Fig. 24).

The variation between nights is even larger (Fig. 11b), with differences in night-averages of over 50 mlx between the peak nights. The variation is not random, but clustered, and corresponds to a large extent to similar weather conditions, as shown by the average cloud coverage per night (red line). These night clusters can go from 1 up to 10 nights, depending on the stability of the weather conditions.

Effect of peaklights

Fig. 12 shows the results of repeated photography at one location, during 2 different nights, without moon. As already shown above, there can be huge differences of brightness depending on the weather. In this example, with foggy conditions (1A-1C), the mean radiance was around 15nW, as opposed to 150nW with dense higher clouds (2A-2C), which is a 10-fold ratio. At this distance, turning on the streetlights (pictures 1C and 2C) had an absolute effect on brightness of the same order of magnitude under both weather conditions, and increased average radiance of about 8 nW. This corresponds to an 30% increase under foggy conditions, but only 5% increase in overcast conditions. Similarly, the car passing by is a lot more visible under foggy conditions than overcast (compare 1A-B and 2A-B). This is mostly due to different contrasts depending on total brightness, as well as a more diffuse and porting glow due to the fog in the series A. In both cases, the maximum radiance measured was drastically increased by the passing car.

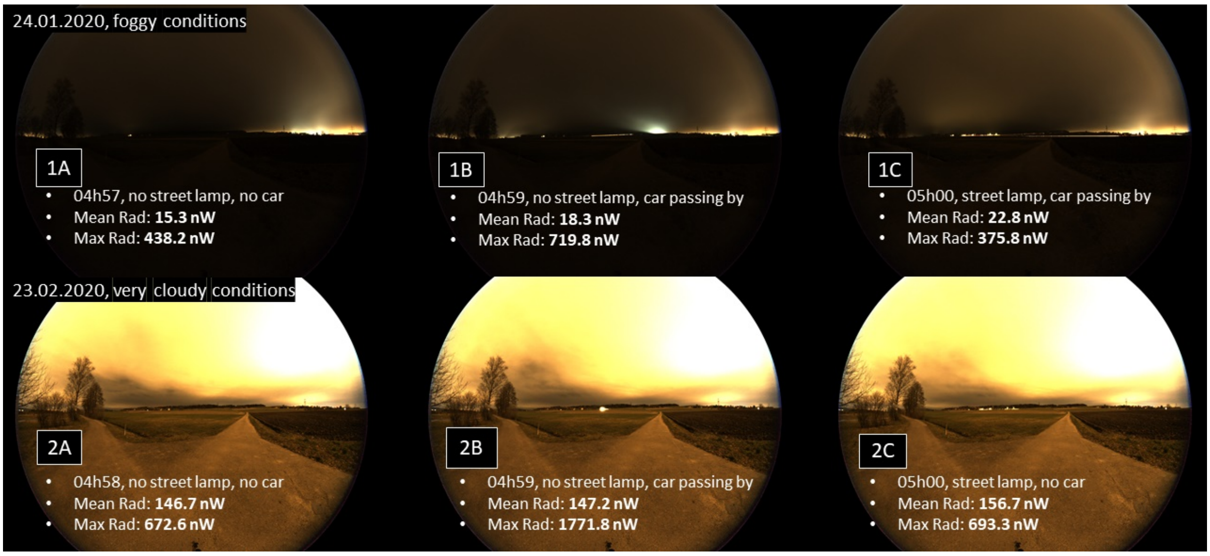

Figure 12: Photographs from location T1.1 under different sky conditions, around 5am. Each series has one picture without any car and before the streetlights of Katzenrüti (center of image) go on (A), one with a car passing by and without the streetlights (B), and one without any car, but with streetlights on (C). The mean and max Rad refer to the measured green band radiance, in nW/sr/m²/nm.

Spatial variation: photography transects

A total of 24 photography series were taken, during 10 different nights between 20h and 06h. One series was removed because of changing weather conditions. I present the full sphere average radiance values per series and location below, as well as a description of the transects. For all transects, I represent each photography series with coloured lines as well as the metric that correlates best with the results data (dotted black line).

Transect 1 (Fig. 13) has a gradient of distance to light sources, were location T1.4 (right side of figures) is the closest (Autobahn + Autobahn rest area + Settlements). The largest differences between the locations are the vegetation and trees nearby, especially at T1.1 and T1.2 (left side), which reduce sky visibility. Lower sky visibility seems to correlate very well with lower radiances in all series, apart from the cloudy-foggy series (yellow), for which the distance to light sources seems to be stronger than sky visibility, and thus steadily increases with closer distance to light sources.

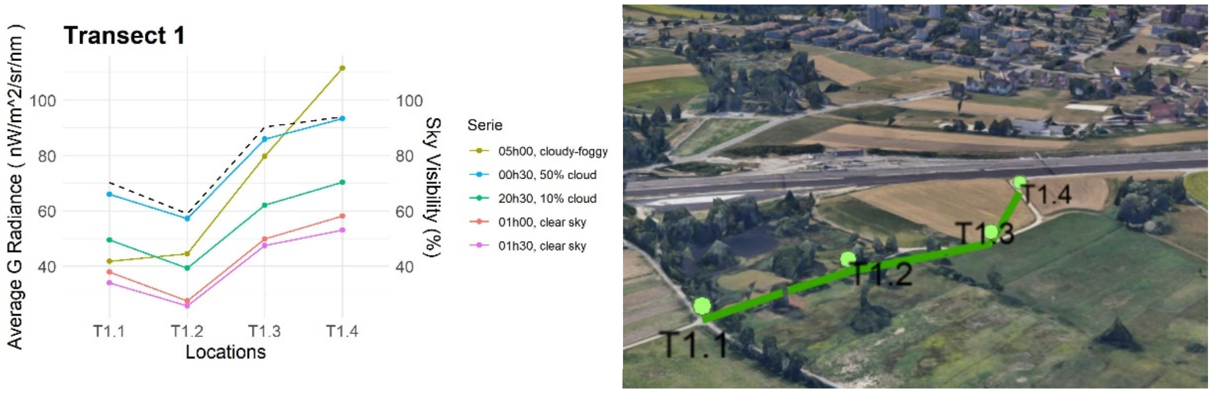

Figure 13: Photography transect 1. The coloured lines represent single photo series from different nights. The dotted black line represents the sky visibility at each location. This metric can also be deduced from the map (presence of trees and bushes).

Transect 2 (Fig. 14) has a strong gradient of proximity to light sources, from close proximity at T2.1 on the left side of figures to further away at T2.9 on the right side. Moreover, T2.1-T2.3 have a high sky visibility and thus receive direct lightning from Affoltern, while T2.4-T2.9 don’t have a lot of direct light emissions. This didn’t seem to affect the measured mean radiances. The only strong gradients in radiance were found under cloudy-foggy conditions. Else, the radiance distribution is rather homogeneous (only with a slight decrease correlated with distance to light source under clear sky conditions). The yellow series (04h30, cloudy-foggy) has higher radiances than the clear sky series close to Affoltern, but lower radiances further away, which can be seen as a darkening effect.

Transect 2 is the transect with the highest ratios between cloud and clear sky measurements. This should not be related to the transect itself, but mostly to those specific series with particularly bright or dark nights. The average ratio is 10-12 times brighter with 100% cloud cover than under clear sky, and can go up to 18 times in the most remote location of this transect (T2.9), when including fog data.

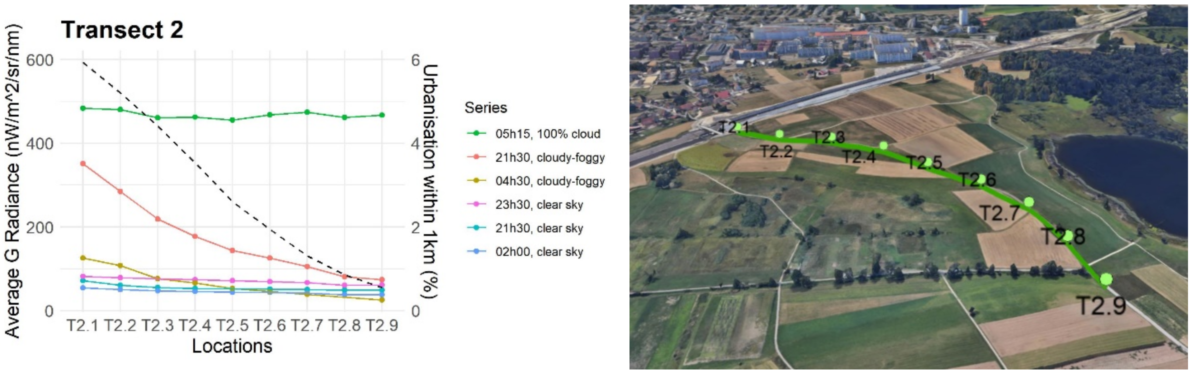

Figure 14: Photography transect 2. The coloured lines represent single photo series from different nights. The dotted black line represents the % of built-up area within a buffer of 1km, at each location. This metric can also be deduced from the map (visual proximity to settlement).

Transect 4 (Fig. 15) is a very strong gradient of distance to settlement, T4.1 being the closest (left side of figures). T4.5-T4.7 are adjacent to the forest, T4.5 and T4.7 being at the corner (similar sky visibility between each other), while T4.6 is on the side (even lower sky visibility). Thus, those locations have a lot smaller sky visibility than the rest of the transect, which correlates very well with the lower radiances. This is particularly visible in the violet series (100% cloud), with a “hole” in radiance at locations T4.5-T4.7. T4.1-T4.6 receive direct light emissions, while T4.7-T4.8 are “hidden” by small slopes and are only lit by indirect sky-glow. However, this doesn’t correlate with the data. In a general way, distance to settlement correlates with radiance only in the cloudy-foggy series (yellow and blue), while clear sky and 100% cloud have more constant values (violet and red). This is the same effect than observed in transect 2.

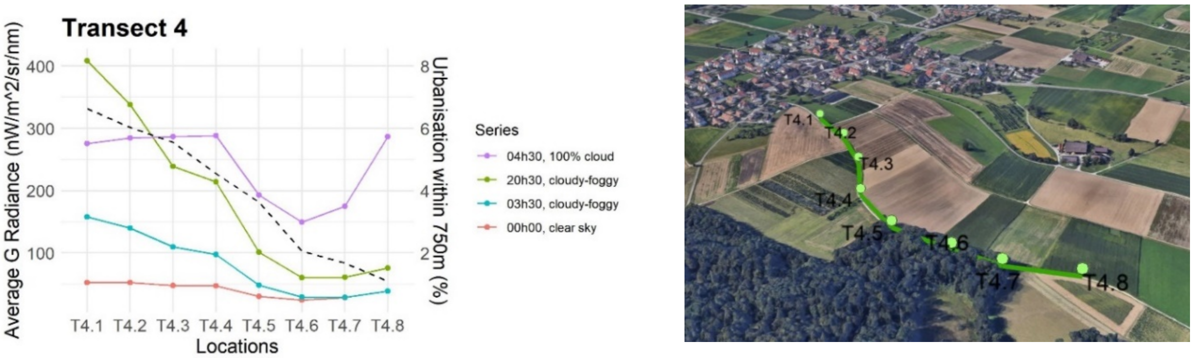

Figure 15: Photography transect 4. The coloured lines represent single photo series from different nights. The dotted black line represents the % of built-up area within a buffer of 750m, at each location. This metric can also be deduced from the map and the visually obvious proximity to settlement.

Transect 5 (Fig. 16) shows an alternance of directly lit and “hidden by the relief” locations. Locations T5.2 and T5.4 are the most exposed ones. T5.3 doesn’t receive any direct emissions. T5.1 does from the North (lower left corner of map), and T5.5 from the South (upper right corner). Overall the light emissions are a lot stronger in the South (Affoltern) so this transect is a combination of (in)direct exposure and distance to light sources (T5.5 beeing the closest, on the right side of figures). The fact that a location is exposed to direct light emissions or not doesn’t seem to affect the average radiance, independently of the weather. Most relevant at this scale is the proximity to Affoltern, but only under cloudy-foggy conditions. In overcast conditions, the radiances, as observed as well in transect 2 and 4, are higher and stay constant, independently of distance.

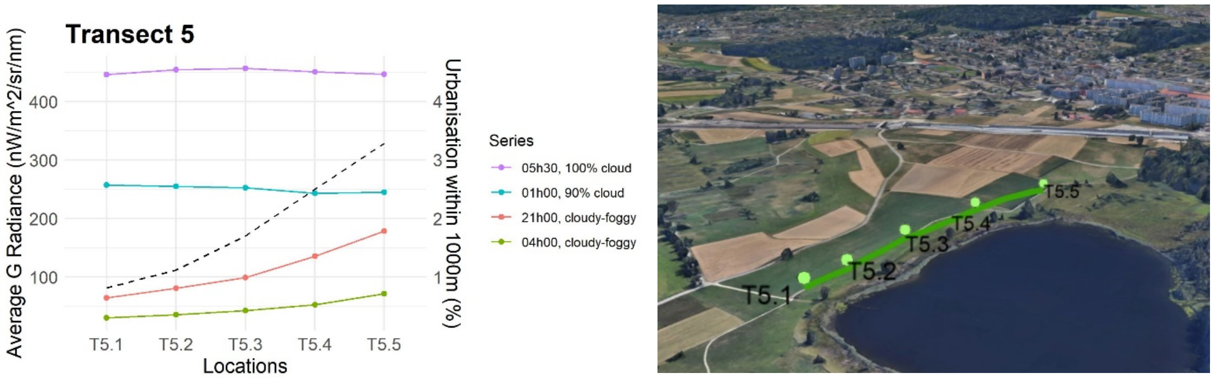

Figure 16: Photography transect 5. The coloured lines represent single photo series from different nights. The dotted black line represents the % of built-up area within a buffer of 1km, at each location. This metric can also be deduced from the map and the visual proximity to settlement.

Comparing luxloggers and full-sphere photography

At each long-term monitoring site, the radiance values from the photographs were compared with the average values of the specific luxloggers, from five minutes before to five minutes after taking the photograph. If there are no lower sensitivity problems from the loggers, the ratio between the two measurements methods should be the same for the whole range of brightness. In this case, the ratio seems to be constant only for radiance values higher than 80 nW, which corresponds to approximately 35 mlx measured by the Luxloggers (Fig. 17).

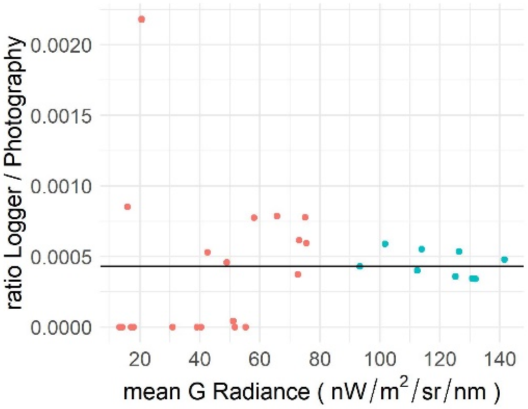

Figure 17: Ratio between the measured Illuminance from the luxloggers and the radiance values from the Photography, plot against the photography measurement values. Blue dots have a Radiance > 80 nW. The black line represents the mean of all blue dots.

2.4 Discussion

My results showed the variation of light pollution that can be found in the Katzensee area, both depending on spatial and temporal factors. At the spatial scale, factors impacting light levels were identified for 3 different weather conditions, and generally related to proximity to settlement. At the temporal scale, large variations between nights and within a night were shown, weather fluctuations being the main cause. Even if the lunar cycle (expected higher brightness in fuller moon phase) could still be observed based on light measurements, in specific nights it was strongly disrupted. I also showed an example of how streetlights or passing cars can affect overall luminosity.

In this part, I will contrast these results with findings from other authors and places and analyse their significance. I will look critically at my methodology and suggest possibilities for measurements in future research projects, based on the results and my experience. As already mentioned, the goal of this study is to provide the practice with the necessary information for enabling actual mitigation of light pollution in the field. Therefore, I will also shortly take away my “scientist cap” and talk as a well-informed involved citizen to integrate the findings of this study into a greater societal context and offer a few recommendations for the practice.

Effect of weather on light pollution

My data supports the well-known fact that in any light polluted area, the presence of clouds amplifies brightness in the field. A full theoretical model for this effect was proposed by Kocifaj (2007), and was well supported by field studies, such as from Kyba, Ruhtz et al. (2011). Interesting is the observed amplification factor (AF) of clouds, which is the brightness ratio between nights with and without clouds. In Katzensee, those approximate 10-12 times. This corresponds very well to a study site in Berlin which was classified as urban (Kyba, Ruhtz et al. 2011). Later findings of an international compilation of monitoring data (Kyba, Tong et al. 2015) report AF values for different urban, suburban and rural sites, ranging between 0.2 and 18x. Out of 52 studies sites, Katzensee would rank in the “best 10” in highest AF. Comparing the reported AF and clear sky brightness, we would expect the Katzensee to have a clear sky of 19-20 mag/arcsec^2, which is what the transformed photography data indicates as well. Judging from this, Katzensee can be classified as a particularly bright suburban area. This fits well with what we observe from the Zürich cantonal long-term light monitoring in 3 locations, where Katzensee shows intermediate values between the urban Zürich centre and the suburban (but close to the airport) location in Winkel (AWEL 2017).

My results show that such a high AF, combined with varying weather conditions over a month, can strongly impact the perceptibility of the lunar cycle. This means that based on measured night average brightness alone, the moon phase cannot always be safely identified. In other words, some nights without moon are markedly brighter as some nights with full moon. Literature about the specific effects of “non-perceptibility of the lunar cycle” on ecology is poor. However, there are numerous studies that link light or lunar cycle to species biology (see review from Longcore and Rich (2004)). Since a disruption of the lunar cycle represents a strong ecological light disorder, we can only assume that some species and their communities in the Katzensee area are strongly impacted. On the bright side of things, moon has different light properties than ALAN (spectrum, strong point source from above, high contrasts on the ground, ...), and it is unclear how this might moderate the expected negative response to apparent lunar cycle disruption.

Kyba, Tong et al. (2015) have reported increasing AF along a rural -> urban gradient, with a decrease after crossing the city borders. This was also shown by the modelling work of Kocifaj and Lamphar (2014). They reported a peak in AF around the outer edge of a city, which then steadily declined with increasing distance. The behaviour of AF within the city is more complex and less foreseeable. Therefore, for suburban and rural areas, the AF could be used as an interesting measure for assessing the degree of light pollution. More ideas to the possible use of AF can be found in Appendix G.

Spatial variation

In a general way, proximity to settlement/light source increases brightness on the ground. The first part of this thesis showed that this effect is very scale-dependent, and that a big settlement far away can have the same effect on average brightness than a small settlement close-by. This scale-dependency was demonstrated while using upward radiance as measured by satellites on clear nights.

Part 2 as well investigated these scale-dependencies but using ground-based data under different weather conditions. The results contrast with the findings of the first part. Indeed, no single general spatial relationship was found. On the contrary, the transect (n°2, 4, 5) analysis suggest that the effect of settlements of different sizes and at different distances vary depending on the weather conditions. In overcast or clear sky conditions, we observe little variation between the locations within the Katzensee. This implies that the observed light levels under those weather conditions are not as much influenced by nearby small settlement as by the overall surrounding areas, which at the local level are a given constant. Around the Katzensee, those high light emissions constants would be Zürich, Zürich North or the Zürich airport, which lays only 4km away and which influence is clearly visible in the field (see Fig. 23 in Appendix E). Those results are not surprising given other studies that modelled (Kocifaj and Lamphar 2014) or measured (Kolláth 2010, Biggs, Fouche et al. 2012, Pun, So et al. 2014) that the effect of a big settlement could be still considerable even at great distances. Under foggy or only partially cloudy conditions, however, the brightness on the ground is more dependent to close-by light sources. This is particularly visible in transects 2 & 4, with very particularly bright conditions within close distance to light sources, but where a clear decrease of brightness with increased distance is observed. This decrease is very strong and even led, in one of the most remote locations of Katzensee (T2.9, see Fig. 8), to a darkening compared to the conditions under clear sky. This scale-dependency of fog effect was not reported in a study in Catalonia, where it was shown that fog had a large homogeneous brightening effect in 2 highly polluted areas (Ribas, Torra et al. 2016). In this case, the authors generally related fog episodes to higher brightness, whereas I demonstrate that fog specifically influences the spatial relationship between brightness and light sources in close to very close vicinity. In a general way, even if this decrease of brightness with increasing distance is obvious, it is not clear from the data whether it is linear or exponential, as one might expect. Repeated series of transect 4 (especially a locations T4.1-T4.4) or the establishment of a new transect could help to clarify that. For the practice, this implies that reducing average brightness within the Katzensee (or any other NSO with similar characteristics) under clear sky or overcast conditions cannot be efficiently done with local mitigation measures. Instead it rather needs an overall reduction of lightning in the whole region (e.g. a shutdown of the airport). However, under foggy or partially cloudy conditions, reducing the adjacent light emissions (for example within a buffer of 1km) should be very efficient for reducing average brightness.

Results from transects 1 and 5 show a great influence of sky visibility on the total average radiance. This is not surprising, since landscape objects such as trees, bushes or hedges often appear darker in comparison with the brightly lit sky, and thus contribute to overall darkening (see example in Fig. 22 in Appendix E). Even if this is not surprising, it suggests that highly structured areas should be less affected by surrounding ALAN, for example by showing some local darker patches, depending on the landscape structures present. Combining network theory and light pollution, I think that it could be important to include local light variations in potential connectivity models for nocturnal species. This would be an excellent subject for future studies and could promote the usefulness of landscape infrastructure for light pollution problematics.

I would like to emphasize that these reflexions on sky visibility are also valid for forests. From the application of the Beer-Lambert law on forestry[9] and numerous field observations, we know that light on the ground can be reduced by up to 99% (in the case of a very dense *Picea* stands) (Kimmins (2004) in Bugmann (2016)). This should be considered when assessing light pollution in forested areas. As an example, Kienast and Weiss (2019) showed that a wide part of the swiss forests are highly light polluted. But it should not be forgotten that even if all previous results are valid above canopy-level (e.g. amplification factor with cloudy conditions, scale-dependency, lunar cycle disruption), there is an exponential decrease of brightness as one penetrates the canopy towards the ground, which probably leads to a very strong reduction of ALAN effects on ground-dwelling forest species.

Peaklights

Most of my results base on average brightness (averaged values over time and/or over the full sphere), and the above discussion was done with respect to this. In fact, the present study gave very little weight to investigating the effect of "peaklights", which I defined as light sources that are particularly bright on a small portion of space (e.g. one streetlight or isolated lamp) or time (e.g. one passing car, that briefly illuminates an area). However, those peaklights can affect the whole landscape picture (see Fig. 12 and example in Appendix E) by changing the local brightness maxima, and one should not forget that peaklights can have a strong ecological negative impact, even while further than 500m away such as in this case (for strong intermittent lights, see Foster, Algera et al. (2016); for spatial peaks, see e.g. numerous references in Longcore and Rich (2004), Hölker, Jechow et al. (2014), Manfrin, Singer et al. (2017)). The results of my repeated photography suggest that passing cars and streetlights have a strong effect on local brightness peaks, even if the average brightness isn't dramatically increased. Even if their absolute luminance stays the same, temporal or spatial local maxima are better noticeable under dark conditions, because of enhanced contrasts (see good examples in Fig. 12 and Appendix E). Therefore, even though there are no findings in the literature about this, I hypothesize that the relative impact of a single light source (local or temporal maximum) is stronger in darker conditions or darker areas. Especially when applying the precautionary principle of the canton, this is very relevant to the practice, which should not neglect this type of direct light pollution in close vicinity to else relatively dark NSOs.

As mentioned in the first part (1.4), this type of light pollution cannot be detected using satellite imagery and needs field assessment, which is time and energy consuming. However, unless one wants to make precise quantitative assessments, I think the human eye is a sufficiently good instrument to gain good insights in an area, which would be very well compatible with a larger-scaled citizen science project. Appendix H offers a few ideas about a possible citizen science approach, especially for monitoring peak lights.

Methodology

The luxloggers set up at the Katzensee seem to give useful and reliable average measures despite the relatively high percentage of measurements "zero". As expected from any technical device however, below a certain threshold of light intensity, the loggers fail to give precise enough measurements. In the case of the MSR145WD, this threshold was found to be at ~35mlx (or 80 nW green band average radiance). Below this threshold, the measured values are not correct anymore. Regretably, this threshold is a lot brighter than the brightness of a natural dark sky. While this is not an issue during most nights in particularly bright sites, such as the Katzensee, I expect the luxloggers to fail giving

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[9] $S = S_0 \cdot e^{-\varepsilon \cdot LAI}$, where S is the radiance on the forest-ground, S_0 the radiance above forest, ε the absorption coefficient, and LAI the Leaf Area Index of the forest. This shows the exponential decrease of light intensity as one penetrates the canopy.

reliable data in darker nights or darker areas (e.g. more remote locations or forest). In those cases, data could still be used for example to assess the brightness of the brightest night in a month, but not for questions needing more precise data, such as determining the amplification factors (from clouds). It is to note that the threshold of 35mlx is valid for the mean measurements of two luxloggers pointed towards Zenith for ten minutes. It can be that using more luxloggers or averaging over a longer period of time enables accurate measurements under this threshold. On the other hand, using only 1 logger should raise this threshold.

The full-sphere photography method has already been tested by several authors and was described as reliable and accurate (Duriscoe 2016, Hänel, Posch et al. 2017, Jechow, Kollath et al. 2017, Jechow, Kyba et al. 2019). The major difficulty of this method is the calibration phase but for many photographical devices, already existing calibration data can be used, which is what I did in this study. I observed that the computed mean radiances are very little sensitive to the chosen exposure, and seem to be very replicable. The use of two photographs in opposite directions, compared to one single picture toward Zenith, gives more spatial information for more advanced uses, is visually more explicit (e.g. to show examples to the public), and allows to get more precise values around the horizon, especially where light sources are present. On the other hand, it needs more storage space and is a bit more time-consuming, so one might consider the alternative depending on the resources and goals. The computation of other indicators (for example measures of the brightest portions of the sky, see Duriscoe (2016)) needs more careful photography setup, especially to avoid overexposure. DiCaLum is a very interesting open-source Octave library, which is very flexible and allows diverse applications. In this study I only computed the all-sky average green-band radiance, but it could be very interesting to compare with the other bands, compute illuminance or perform more complex image analysis to gain more spatial information. One big advantage of full-sphere photography is the reproducibility and comparability of the results with other studies or measurements systems (such as Sky Quality Meter, different luxloggers, etc.). Overall, I think that this photography method is very promising, and I would favor it in upcoming studies or projects. Given the easy acquisition of the necessary material and the well-reproducible results, one could possibly think of using photography in a larger citizen science project (but see counter-indications in Appendix H).

Lastly, the field work took place between December 2019 and February 2020. However, winter is for many species a resting season, and most of the biological activity is concentrated in the spring and summer months, with a particular vulnerability to disturbance during the breeding season (starting mid-March, many restricted areas during breeding season; see as well Wilsey, Taylor et al. (2019)). Even if the light regimes in the middle of the night should be constant during the whole year, the nights are considerably shorter during the summer. This implies that the negative impacts from ALAN in the summer can only happen later in the evening or earlier in the morning. In mid-June for example, the night won't start before 11pm and ends at 4am. Thus, all the negative impacts due to lightning from the traffic rush hour will be inexistent. The same applies for house lightnings, which might already be turned out by 11pm and won't be turned on before later in the morning. Another point is that the weather conditions may vary a lot between seasons, with possibly less cloudy or foggy episodes in the summer (personal observation), and therefore different brightness. Lastly, a cold episode in January 2020 provoked frost, and during a few nights a very thin snow cover was present. This should lead to brighter measurements than expected during milder months (Jechow and Holker 2019). This possible overestimation of the impacts of light pollution is a very positive error for the practice, because keeping the precautionary principle in mind, generalising my results for the whole year should keep us on the safe side of conservation.

Conclusion

This study is the first of its kind to combine both satellite data and *in situ* measurements to assess the extent of light pollution in an area, in this case the canton of Zürich. It proved to give consistent and complementary insights into questions of spatial and temporal light pollution variation. Even if nothing close to more extreme areas, the canton of Zürich is a fairly light-polluted area, and in particular suburban nature reserves can experience very bright sky conditions.

What now? Apart from further research (see suggestions in discussion and in the literature, in particular Hale and Arlettaz (2019)), I think it is time to put into practice the present knowledge to further implement light-protection measures into conservation plans, especially in explicitly protected nature areas. My research gave interesting insights about the local variation of light at a temporal and spatial scale, and therefore can support the practice to work for mitigation purposes at the local level. The only efficient way to reduce ALAN effects in nature reserves is to steer light emissions that lay within close distance to the area that should be protected (up to 1 km). Such a buffer zone would need a very specific design to ensure optimum effect. Even though a whole project could (should?) be led to optimise the specifications, my work suggests focusing on following points:

- Reducing overall brightness: a strong effect was shown from settlement as far as 800m away. The buffer could be extended to 1km to include particularly strong emissions in this range and stay on the conservative side of things. Within this range, all types of light sources should be mitigated, which can be done e.g. through diminishing, switching off, blending, or introducing of threshold values. The possibilities to do this are numerous and can be found in different guidelines (e.g. national Swiss guidelines in BAFU (201x)).
- Reducing peak brightness: a non-negligible effect was detected at 550m. The buffer for this type of light pollution could be of 500m and should give attention to fixed direct light emissions from streetlights or private houses and passing motorized traffic (even possibly passing bicycles within the area). Those peak light sources are very specific to one place, and implementation should not be done without knowledge of the local conditions.
- As stated for peaklights, knowledge of the local conditions is necessary for efficient measures. This knowledge could potentially be gained by the use of aerial photographs such as available in the canton of Geneva, or else needs field observations, be it from a citizen or professional basis. The canton should think about how to ensure access to local knowledge.

Moreover, my results and experience with the methodology enable to highlight following technical points for future projects or research:

- The MSR145WD luxloggers are not sufficiently sensitive to use in areas darker than the Katzensee, such as rural nature reserves or forested areas. For questions needing high temporal data resolution, they might be used in brighter areas.
- The full-sphere photography method is robust and should be thought of for further measurements, given there is good quality calibration data available. To make single measurement more comparable between locations, photography should be done under clear sky conditions, or in especially bright conditions under full cloud cover. For a more integrative assessment of a single locations, I recommend using repeated photography along transects, which might be placed along walking paths. It is important that each time the

camera be positioned at exactly the same locations and positions (hemisphere or full-sphere photography might be considered, see discussion). Transects should reflect single gradients as well as possible, to isolate effects. Lastly, it is possible to use time-lapses to get high temporal resolution from photography data.

- To better determine the specifications of a light buffer-zone or to assess the efficacity of newly implemented measures, transects should be done at least once with clear sky and once with full cloud coverage, but focus should be put on intermediate conditions, such as fog or partially cloudy conditions.

As a final note, I would like to say that I strongly support the work of the environmental protection authorities and think their work is of upmost importance, not only at the national but also at the cantonal level. I would feel very grateful if my work can help in the creation or adaptation of policies to further protect the environment from light pollution. However, I wish that this responsibility shift towards the greater instances doesn't lead to a diminishing of the personal and community-based responsibility feeling. I would like to remind the reader that local engagement and bottom-up initiatives are in many respects the very founding of efficient environment conservation and should in no way be forgotten: Light pollution is an issue that concerns all of us.

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Appendix

Appendix A: Technical memo on light

Light properties and measurements are not straightforward to understand for readers without prior knowledge on the subject. Here I briefly summarize the main physical quantities named in this study to facilitate understanding, but do not aim to give a comprehensive and physically strictly correct account. For interested readers, a more extensive overview of radiometry and photometry and further literature is given in Jechow and Holker (2019).

Radiance: Outgoing energy flux from a surface as seen through a solid angle, in $\frac{nW}{sr\ cm^2}$. For the sake of reader, I generally simplified the units to "nW" in the text. If not specified, the energy is measured over all wavelengths. Upward radiance concerns radiance going to the zenith, as measured from above with satellite data. For the VIIRS DNB satellite data I used, radiance is measured at ~500-900nm. Radiance is also the measured quantity using fish-eye photography.

Irradiance: This is the equivalent of radiance, but as seen from the "other side". It is the incoming energy flux. In other words, it is how much energy is perceived from a given location.

Luminance: This is the same concept as radiance, an outgoing flux. But here we don't talk about energy flux, but luminous flux (i.g. number of photons per time and surface. Units: $\frac{lm}{sr\ m^2} = \frac{cd}{m^2}$ ($1\ \frac{W}{sr\ cm^2} \approx 6.83 \times 10^6\ \frac{lm}{sr\ m^2}$). Else said, this is the outgoing photometric flux from a surface.

Illuminance: This is the same concept as irradiance but applied to luminance. In other words, this is the incoming luminous flux, i.g. how much light is perceived from a given location, in lux (lx).This is the measured quantity from the luxloggers.

Magnitude: It is a quantity originally used in astronomy and usually refers to how well can the stars be seen in the sky at Zenith, or to the magnitude of the faintest visible star. The values are given in $\frac{mag}{arcsec^2}$, on a logarithmic scale, where 22 mag/arcsec^2 is a very dark sky and 16 mag/arcsec^2 a very light polluted sky. This is the quantity measured by Sky Quality Meters[10], which have been used in many studies.

Brightness: whenever not confusing in the text, I preferred to use the term brightness to generally describe how bright a location or source is, independently of the incoming vs outgoing perspective.

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[10] Device to measure zenith sky brightness, see http://unihedron.com/projects/darksky/, accessed 22.04.2020

Appendix B: level of importance of selected NSO

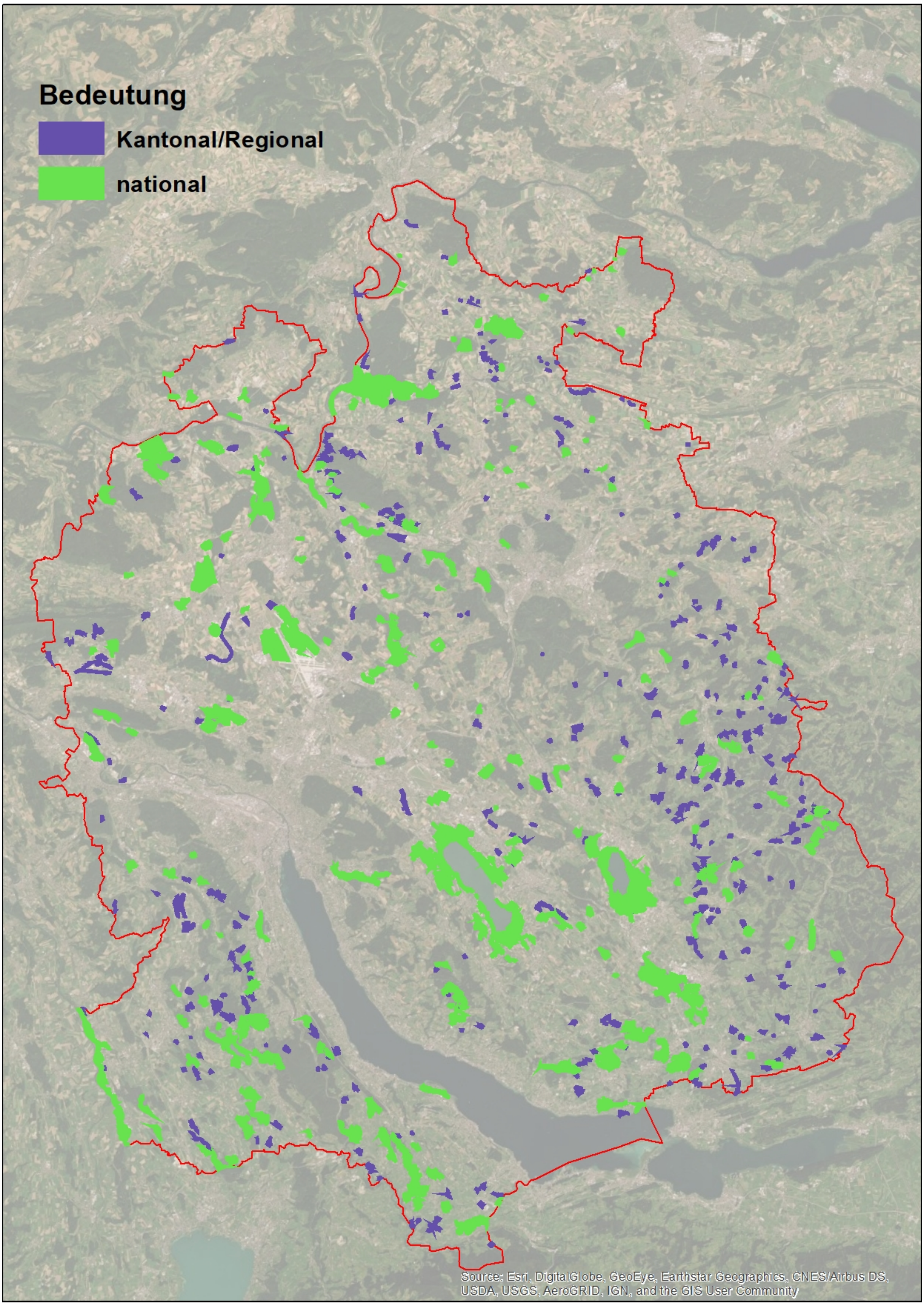

Figure 18: Level of importance of all selected nature areas in the canton of Zürich.

Appendix C: Modelling VIIRS in NSO

```
Radiance ~ I(PopDens1000^2) + I(PopDens5000^2) + log(DistGeb) +
    log(DistLamp) + I(BuiltUp^2)

                   Df Deviance    AIC
- log(DistGeb)      1   96.963 228.17
<none>                  96.609 228.77
+ Bedeutung         1   96.561 230.58
+ log(SHAPE_Area)   1   96.595 230.72
- log(DistLamp)     1   99.434 237.91
- I(PopDens1000^2)  1  116.944 306.95
- I(BuiltUp^2)      1  118.009 311.15
- I(PopDens5000^2)  1  167.803 507.48

Step:  AIC=229.22
Radiance ~ I(PopDens1000^2) + I(PopDens5000^2) + log(DistLamp) +
    I(BuiltUp^2)
```

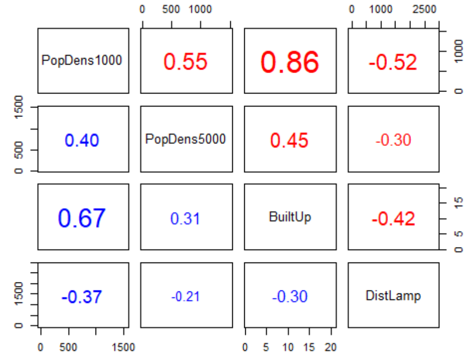

Figure 19: (left) Last step of the stepAIC procedure to select the best model fit, showing model's residual deviance and AIC values for any term deletion or adding. (right) Correlations (Spearman in red, Kendal in blue) between variables of the final model. DistGeb = Distance to next building, Bedeutung = regional vs cantonal relevance, SHAPE_Area = Area of NSO, DistLamp = Distance to next streetlight on a cantonal street, PopDensXXXX = Population Density within XXXX meters of the NSO (n/km²), BuiltUp = % of built-up area within 1km around the NSO.

Appendix D: Effect of landscape metrics on radiance

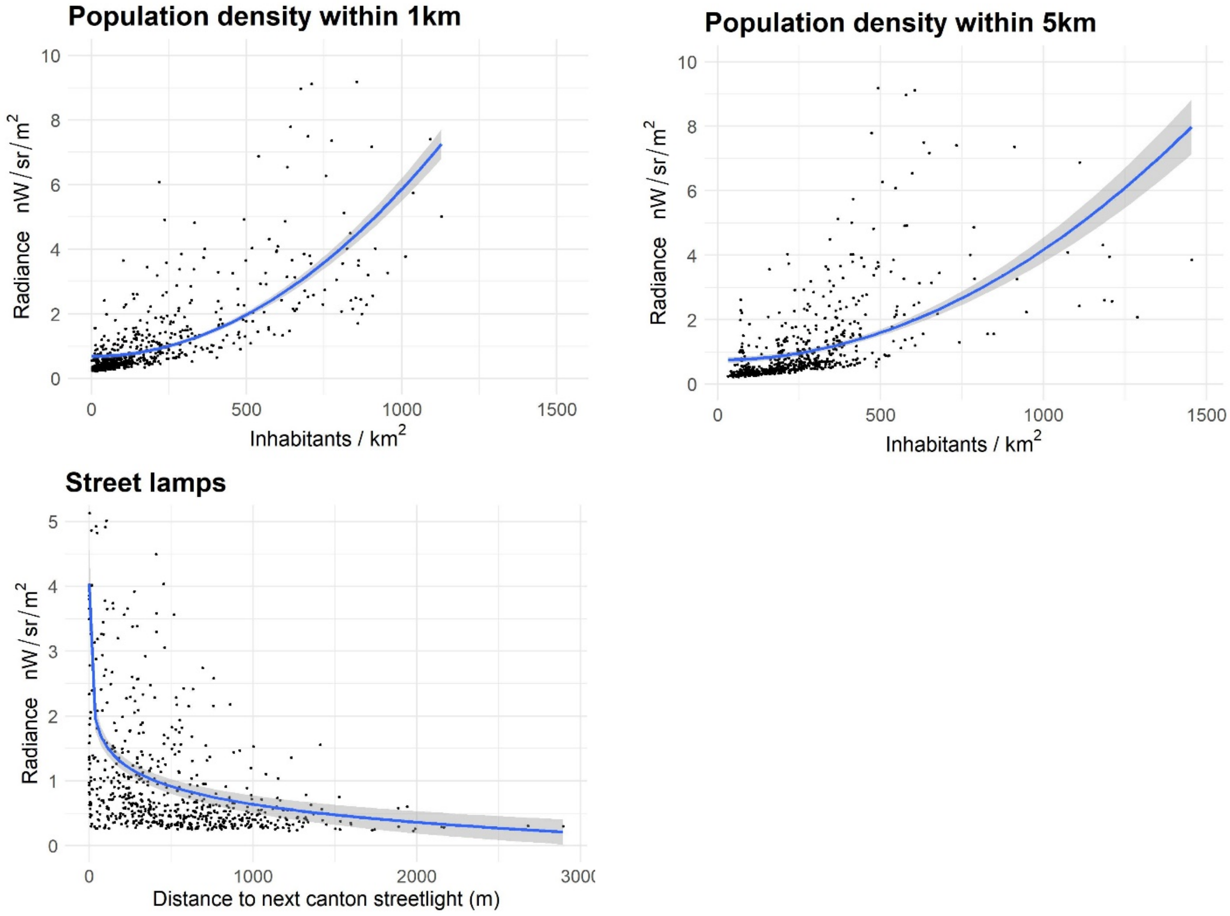

Figure 20: Effect of population densities (within 2 different buffers) and distance to next streetlight on a cantonal street on radiance in NSOs

Appendix E: Photography examples

Figure 21: photography at location L3 with a bright moon. With this (a part from the moon) relatively dark sky, the single lamp at the other side of the lake (at 270m distance, middle of picture) is particularly visible and strongly illuminates the adjacent reed area. The trees on the right side do not contrast a lot with the sky.

Figure 22: Same location as Fig. 21, but with 100% cloud cover. The light from the other side of the lake (middle of image) is less contrasting in this very bright environment, and the trees on the right side appear very contrastingly.

Figure 23: Under overcast conditions, the brightening effect of the small settlement 550m away with 4 streetlights (middle of image) is negligible in comparison with the skyglow from Zürich North and the Zürich airport (upper-right corner). Location T1.1

Appendix F: Time series analysis for the mean illuminance of all 10 long-term locations

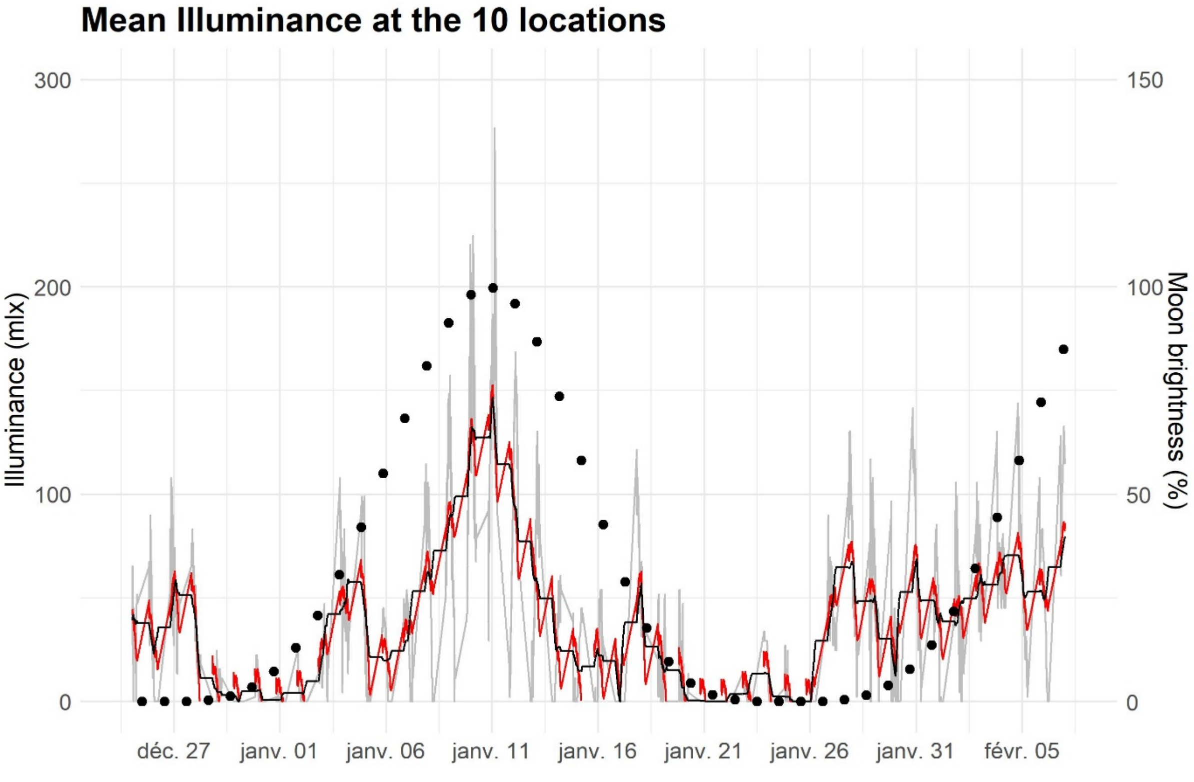

Figure 24: time-series analysis of the mean Illuminance for all sites. The red line represents the modelled intra-night variation, the black line the trend over all nights (inter-nocturnal variation) and the grey line the observed Illuminance (random effect). Within single nights, very big "random" variation can be observed, especially with full moon.

Appendix G: Utilisation of amplification factor (AF) in future projects

Depending on the light measurement method, giving comparable values can be tricky, especially if measurements are done by many different people. Indeed, the variety of tools, their calibration, the different measured physical grandeurs and individual usage is problematic for absolute replicable results.

On the other hand, the usage of amplification factor (AF) could give useful and more constant values for comparisons. AF is the ratio of brightness during a full cloud-cover night and a clear sky night, at the same location. This can be computed independently of the measurement method and should vary less than the absolute measurements themselves. What's more, Kyba, Tong et al. (2015) showed that in rural and suburban areas, AF increases steadily along a gradient rural -> suburban, which can be assessed as increasing light pollution. I think AF would be a good proxy to assess light pollution in an area, give reproducible and comparable results, and easily computed independently of the method. Even though more trials with different methods and at different locations are needed to assess this on a more scientific basis, I think it is promising.

Indications to possible methodology: It is important that the methodology is the same, especially when choosing the time for measurements. For both measures (dark and bright night), measurements need to be done without moon (< 10° below horizon). For the choice of the dark night, the stars should be as visible as possible. This can be either subjectively assessed, or measurements should be made during a couple of nights. For the choice of the bright night, I think an opportunistic approach is best. For example, take measurements during three different nights that seem particularly bright, and take the highest measure. For all measurements at one location, it is important that the same procedure be applied (measurement tool, orientation, time during night, etc.).

In the example of measurements using fish-eye photography, orientation towards Zenith would be best. If the tripod doesn't allow for this, any combination of different orientations would be good, as long as they are the same for all pictures.

Appendix H: Possibilities of citizen science for light pollution

There are already possibilities to upload online measurements such as from a Sky Quality Meter[11]. For example at https://www.lightpollutionmap.info/ (see map layers), which doesn't need anything else than a willing user to enter their measurements in a few clicks. This database could probably be adapted to allow for different types of measurements, including from fish-eye photography.

However, I personally doubt the efficiency of such an approach for research or direct conservation purposes. Indeed, getting correct measurements from photography needs good material, is quite time-consuming and would need strict directives to follow. In the case one wants to assess the AF (see Appendix D), a lot of measurements would be needed to ensure data-quality, given the big variability of brightness depending on different weather conditions. Therefore I would not invest too much energy in such a project (NB: I am not an expert in this field, and this is just the impression I have, not based on actual experience related to this.)

On the other hand, I see a lot of potential in citizen science to discover and monitor light sources that have a high relative effect (i.e. that contribute a lot to the local brightness conditions, such as one bright streetlight, see example in Appendix E Fig. 21) and that have mitigation potential (by switching off, blending, reducing light intensity, etc.). As a matter of fact, as stated in the discussion on peaklights, I think the human eye is good enough to detect contrasting light sources (that have therefore a high relative brightening effect), and that an easy methodology could bring useful results for the practice. Anyone could contribute even without any prior knowledge, and the results would allow to get a good overview and visualisation of problematic light sources, to be put at use through local decision-makers (such as a municipality) or for research projects (as data, or as indications for possible locations to be investigated).

Indications to possible methodology: individual manual report in an online database of problematic but mitigable light sources (e.g. a streetlight, a whole building façade, a private lightning system), with information about effect of light source (low effect, middle effect, high effect), responsibility (e.g. municipality, private, firm) and precise location. Short and precise instructions would be needed to ensure data consistency.

Such a database could be set up at the national level. Population awareness for light pollution is growing, and I think there is a lot of potential to engage citizens. However, since actual mitigation measures take place at a more local scale (such as the municipality), those smaller socio-political units could be responsible to "motivate" their citizens. As an example, the first edition of *La nuit est belle!*[12] took place on the 26.09.2019 in the Geneva region. In the first part of this night, most of the public lightning and part of the private lightning were switched off, with multiple sensibilisation events. The event was a big success for growing awareness, as explained in Vares (2019). In a next edition of *La nuit est belle!*, citizens could be specifically asked to report on light sources that could affect close-by nature reserves.

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[11] Device to measure zenith sky brightness, see http://unihedron.com/projects/darksky/, accessed 22.04.2020

[12] https://www.lanuitestbelle.org/, accessed 22.04.2020