Water masses surface temperatures assessment and their effect on surrounding environment

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ABSTRACT

The aim of this study was to evaluate the effect of water masses on the surface temperature with direct impact on the surrounding area. Three systems were used for the study: a fully vegetated system (subsurface flow constructed wetland (CW)), a lake with no vegetation and a lake partially vegetated with *Lemna minor*. Infrared thermography was applied for the different systems analysis, allowing the determination of the surface temperature spatial distribution. In general, the presence of plants and water in the analyzed systems contributed to lowering the surface temperatures when comparing to its surroundings. Differences up to about 22 °C were observed in the temperature between the CW canopy and the surrounding soil, and up to about 19 °C between the lake and the surrounding border. Different plant species (*Canna flaccida*, *Canna indica* and *Zantedeschia aethiopica*) inhabiting the CW were also compared and slightly higher average surface temperatures were observed for *C. indica*. The above mentioned results are relevant in terms of supporting a strategy for water systems inclusion, for example a lake or a CW, in a site as means of having influence in the surface temperature and to some extent in the heat island effect supporting a sustainable environmental management.

Key words | biosystems, constructed wetland, ecosystem services, green and blue infrastructures, heat island effect, infrared thermal imaging

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INTRODUCTION

Ecosystems may provide a panoply of services that can be considered as benefits with direct or indirect impact on people. These include provisioning (e.g. fresh water and food), regulating (e.g. climate and water regulation), and cultural (e.g. recreation and ecotourism) services that are connected with human beings and with other supporting services (MA 2005). Biosystems such as constructed wetlands (CWs) and lakes (unvegetated or partially vegetated) have demonstrated to provide valuable ecosystem services (Yang *et al.* 2008; Schallenberg *et al.* 2013). Carbon sequestration and hydrological buffering are considered as an ecosystem service in terms of reducing the climate warming effect (Schallenberg *et al.* 2013). Getting to know deeper the influence of their presence in the surrounding environment is a challenge and deserves further research, especially in a time where the heat island phenomena is being strongly addressed. This phenomena or effect is more notorious in urban areas than their rural surroundings, being influenced by the geographic location and weather patterns. Besides that, the urban infrastructure radiative and thermal properties has a great impact on the local microclimate and the extension of the heat island effect (USEPA 2008). The evaluation of the impact of different surfaces on microclimatic conditions depends on advanced calculation models if plant cover is involved (Chen *et al.* 2011).

Services provided by natural ecosystems can be attained in constructed ecosystem services contributing to human welfare (Yang *et al.* 2008). Each component of the biosystems influences the intrinsic dynamics and consequently the ecosystems services. For instance, plant fill ratio has importance when talking about water temperature in CWs (Hill & Payton 2000). Infrared thermography (IRT) techniques may complement past research concerning the role played by vegetation and water masses, taking in consideration the conversion of solar energy to transpiration and thermal insulation provided by plants.

IRT is a technology that enables the determination of the surface temperature of an object, being non-destructive and

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with no object contact needed. Emissivity is a key parameter to be inputted into the infrared camera, as it is related to the amount of radiation emitted by the surface. It is an optical property that relates the amount of radiation emitted by the surface with the one emitted by a black body at the same temperature. Through the thermal images produced by the infrared cameras it is possible to carry out a qualitatively and quantitatively analyses concerning the surface temperature distributions (Karczmarczyk & Baryła 2013; Barreira *et al.* 2016). Thermal imaging has been used with various purposes related to buildings, for instance, assessing moisture related phenomena in building components (Barreira *et al.* 2016) and assessing the hygrothermal behavior of façades (Freitas *et al.* 2014). It also has great potential to be applied in other fields related to plant science, agriculture, ecology and environment interactions (Costa *et al.* 2013), for instance, it has been used for monitoring the effects of salinity on *Euonymus japonica* (euonymus) plants (Gómez-Bellot *et al.* 2015), for spatial distribution flow paths and transport characteristics of wetlands (Schuetz *et al.* 2012), for assessing temperature pattern along a CW under cool air temperature (Karczmarczyk & Baryła 2013), for remote diagnosis and quantification of plant responses to water stress in the field (Jones *et al.* 2009), in citrus and persimmon trees (Ballester *et al.* 2013) and on the thermogenic blossom of the giant tropical water lily *Victoria cruziana* (Lamprecht *et al.* 2002).

The main objective of this study was to assess the potential of IRT to evaluate the behavior of three different biosystems in terms of the impact of vegetation and water masses on the surface temperatures and surroundings, as possible mitigation of the heat island effect. For that a fully vegetated CW, a lake with no vegetation and a lake partially vegetated with *Lemna minor* were considered. The specific aims were (i) to assess the daily effect of vegetation and water masses in relation to surface temperature, with direct impact on the surrounding area and (ii) to compare the surface temperature of three different plant species (*Zantedeschia aethiopica*, *Canna flaccida* and *Canna indica*) in order to evaluate if it could be a differentiating factor when selecting species for a CW.

MATERIAL AND METHODS

Sites characterization

Three different sites or biosystems, ecological engineered based, were considered for the present studies where presence/absence of plants and type of water system (lake or CW) are distinctive as shown in Table 1.

The sites were located in a rural area dominated by agriculture and forests, specifically within a guest house with a farm – Paço de Calheiros, subject to the same climate conditions (Mediterranean) and solar exposure, in Calheiros – Ponte de Lima, in the North of Portugal (41.806223, −8.566488). According to Köppen classification, Portuguese climate in Minho region is classified as Csb, i.e. temperate climate with rainy winters and dry summers with mild temperatures. Site A is a CW for wastewater treatment with horizontal subsurface flow, completed vegetated with a polyculture (detailed description in Calheiros *et al.* (2015)).

Site B (Figure 2(a)) is a constructed lake with no vegetation, surrounded by a stone border, soil and at a distant plan vineyard, and site C (Figure 2(b)) is a constructed lake, partially vegetated with *Lemna*, surrounded by a stone pavement border and in a second plan a vineyard.

Measurements procedure

IRT was used in order to compare (qualitatively and quantitatively) the surface temperature of the three different

Table 1 | Sites characterization where the IRT image acquisition took place

Site	System	Perimeter (m)	Vegetation	Distance from the IRT camera focus (m)	Observation
Site A	CW	33	Fully vegetated with 3 dominant species: *Canna flaccida*, *Canna indica* and *Zantedeschia aethiopica*	7 2 10	Site A1: zone with plants height approx: 1.70 m Site A2: zone with plants height approx: 0.70 m and with influence of the stone wall Site A3: global view of the CW and the surroundings
Site B	Lake	48	No vegetation	15	Surrounded by a border of a stone pavement, soil and at a distant plan vineyard
Site C	Lake	39	Partially vegetated with *Lemna minor*	12	Surrounded by stone pavement, some trees and at a distant plan vineyard

Three angles (A1, A2, and A3) were evaluated due to the extension of the CW and the presence of a granitic stone wall in one of the sides (Figure 1; Appendix S1 – see supplementary data, available with the online version of this paper).

Figure 1 | Site A: CW vegetated with a polyculture. Three different sites where selected for IRT image acquisition (A1, A2 and A3). The area captured by the infrared camera that was under study is highlighted.

sites, along different periods of the day (from 10 a.m. to 9 p.m. in September-summer time), where the presence of plants and water was a fulcra element, as surroundings of each site.

The IRT camera was set, varying the distance for image acquisition from site to site, in order to embrace the selected perimeter and acquire the thermal images (Table 1). The IRT camera was a Thermo Tracer TH9100 from NEC AVIO with the following basic properties: 320 (H) × 240 (V) thermal image pixels, measuring range of $-20\,^{\circ}$C to $100\,^{\circ}$C, resolution of 0.06 at $30\,^{\circ}$C, accuracy of $\pm 2\,^{\circ}$C or $\pm 2\%$ of the reading, detector was uncooled focal plane array (microbolometer) and a spectral range band of 8 to 14 μm. With this camera it is possible to have a combination of high resolution infrared and visible spectrum images which allows to compare and identify the several elements in the site (water, soil, plants, vineyard and stone border) facilitating the identification of leaves in the images.

Figure 2 | (a) Site B: Lake with no vegetation. The area captured by the infrared camera that was under study is highlighted. (b) Site C: Lake partially vegetated with *Lemna minnor*. The area captured by the infrared camera that was under study is highlighted.

Before the measurements, all calibrations of the IRT camera referred by the maker were performed, namely, reflection calibration (to correct the error by the influence of reflective elements), ambient calibration (to correct the error by the influence of the ambient between the camera and the measuring object) and background calibration (to correct the error by the influence of the background radiation, performed according to Standard ASTM E1862 – 97 (2010), involving corrugated aluminium foil as reflection element). The emissivity adopted was 0.98 for the vegetation (Jones *et al.* 2003), 0.95 for the water (Omega 1998), 0.78 for the soil (Jones *et al.* 2003) and 0.93 for the granitic stone wall (Omega 1998). Outdoor climate conditions during the test campaign were registered: temperature, relative humidity and climate conditions.

Data analysis

During the campaign several thermographs and measurements were obtained from which those presented in this study were chosen as being representative. The qualitative analysis was based on the observation of thermal patterns present in the thermal images. The quantification of the effect of the vegetation and the type of water mass under study (CW completed vegetated, constructed lake with no vegetation and a constructed lake partially vegetated) was carried out based on the comparison between the surface temperature measured with the IRT camera (Tsup (°C)), whose data were statistically processed using the camera software, with the air temperature (Tar (°C)), for each measuring time. The area captured by the infrared camera that was actually analyzed in this study is highlighted in Figures 1 and 2.

Concerning the CW, a comparison related to the evaluation of surface temperature between three different plant species (*Z. aethiopica*, *C. flaccida* and *C. indica*) was also carried out.

RESULTS AND DISCUSSION

Qualitative and quantitative evaluation of the thermal imaging

Concerning qualitative evaluation of the CW site (A), the thermal images shown in Figure 3 exhibit the temperature evolution at site A1 for the five time periods considered. It is possible to verify that the soil surface, in the lower part of the image, is always hotter than the CW, being this fact more notorious in the first four measurements. In the last two measurements (19 h and 21 h) the temperature differences between the soil and the CW are smaller, although at the CW slightly lower, which may be attributed to the specific heat of the correspondent surface materials.

In the thermal images shown in Figure 4, for site A2, it is notorious the evidence of the presence of the granitic wall. Between 10 h and 12 h, the granitic wall presents lower temperatures than the CW. This results from the fact that it is in shadow and thus the wall did not received any direct solar radiation, on the contrary the CW has been already exposed to direct solar radiation at the time of the image caption. Between the period of 15 h and 17 h, the wall and the CW are receiving direct radiation being the temperature always lower in the CW, although the difference is more distinct at 17 h. By the end of the day, when there is no direct solar radiation incidence on the evaluated zone, and at night (21 h), the wall presents higher temperatures, due to its capacity to retain the heat accumulated during the day.

The temperature evolution in site A3 is shown in Figure 5, through the thermal images, for the considered periods of time. The comparison between the temperatures of the soil and the CW is not evident, since the incidence of direct solar radiation is not equivalent for most of the measurements. At 10 h, a section of soil is in shadow as the frontal section of the CW, due to the presence of trees. However, it is possible to admit that temperature will be similar for similar solar incidences, based on the data acquired. At 12 h the soil is completely in shadow as the frontal part of the CW, even so, soil temperature seems to be higher than the CW that is receiving sun. Between 15 h and 17 h the soil and the CW have similar sunlight conditions (soil and CW receiving sun and frontal section of the CW in shadow, due to trees). The soil displays surface temperatures clearly superior to the frontal section of the CW, which is expectable because that section of the CW is in the shadow. However, comparing the soil temperature to the top of the CW that is exposed to direct solar radiation,

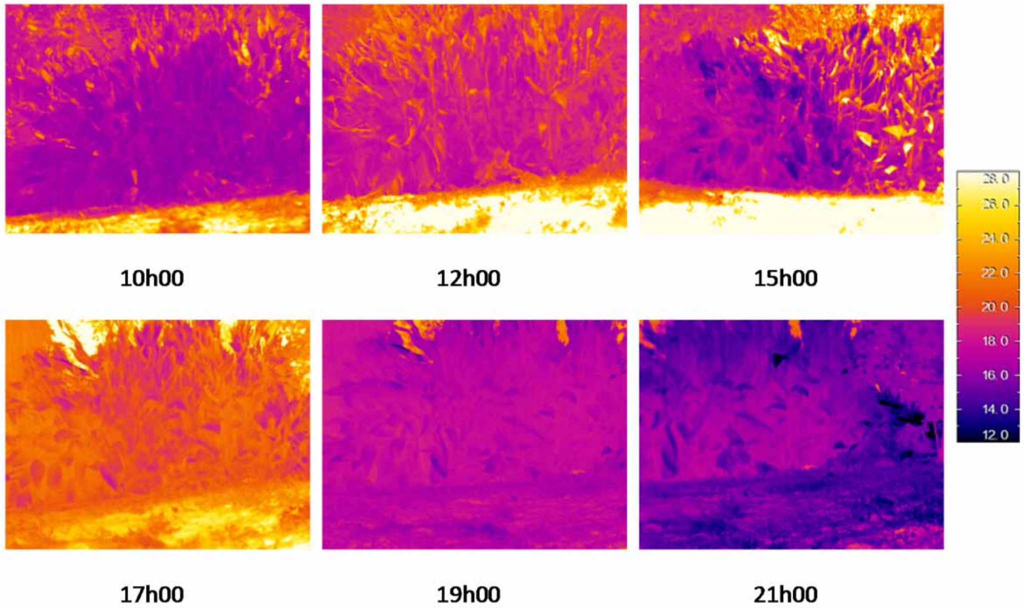

Figure 3 | Thermal images retrieved from site A1 – CW, at different periods of time (h).

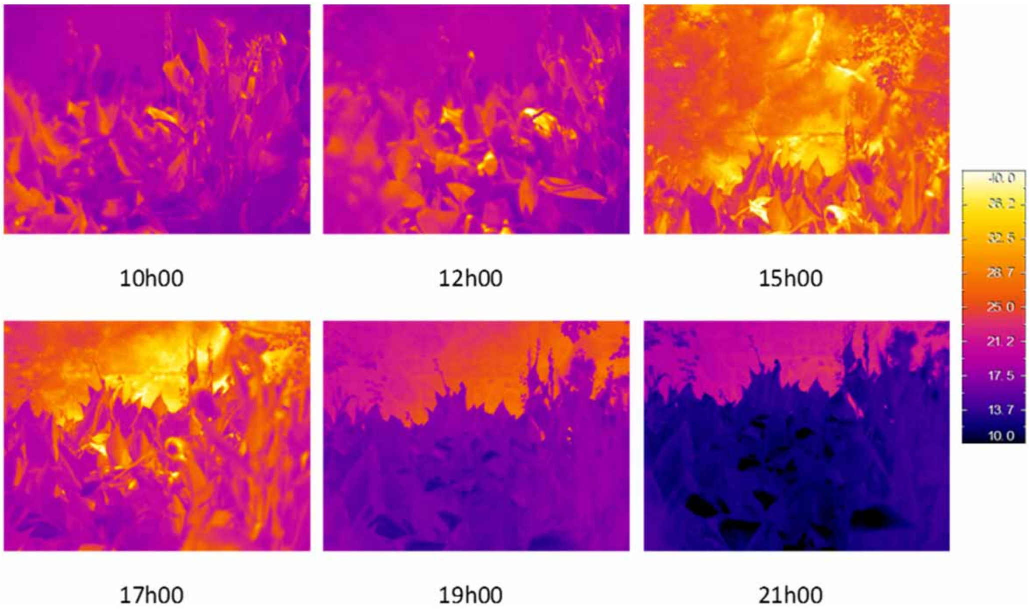

Figure 4 | Thermal images retrieved from site A2 – CW, at different periods of time (h).

surface temperature is still higher, in agreement with the thermal images presented in Figure 5. At 19 h the frontal section of the CW has a similar temperature to the soil as the plants are receiving direct solar radiation, being the soil with shadow. This factor may also have had influence on the 21 h temperatures. Having in consideration the three localizations (A1, A2 and A3) from site A, the last one is the least interesting in terms of results since there was a strong influence of the shadow and trees.

In relation to Lake site (B), with no vegetation, Figure 6 reveals that the water mass has always temperatures lower than the surroundings (soil and vineyard), even when clouds cover the sky and are reflected in the water (as seen in Figure 2(a)), increasing the surface temperature measured by the camera (apparent temperature). The only exception is at 21 h that may be related with an increase of the cloud cover, with the capacity of the water to retain heat accumulated during the day or the humidity effect. In general, the

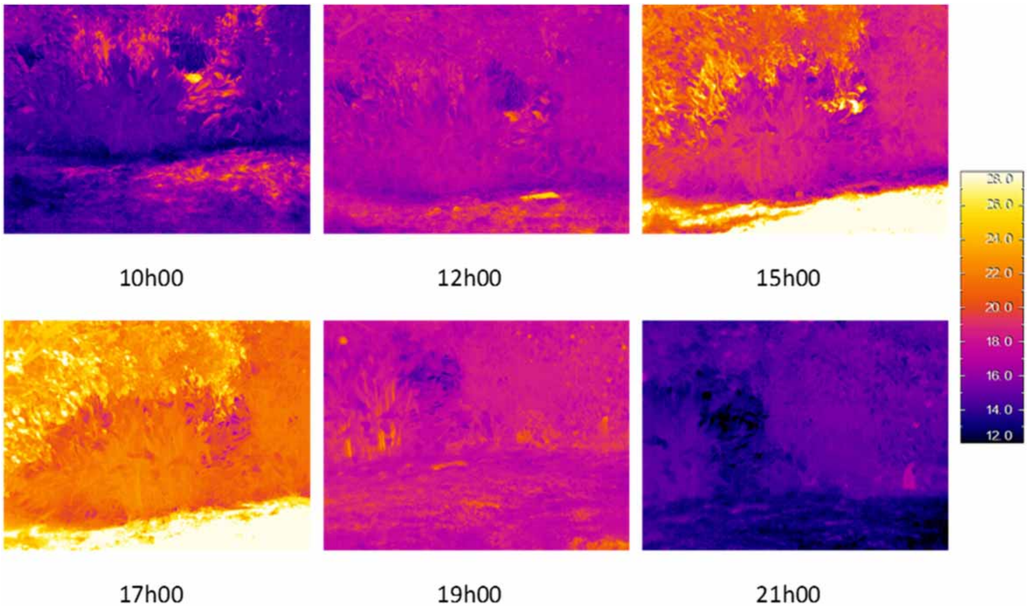

Figure 5 | Thermal images retrieved from site A3 – CW, at different periods of time (hours).

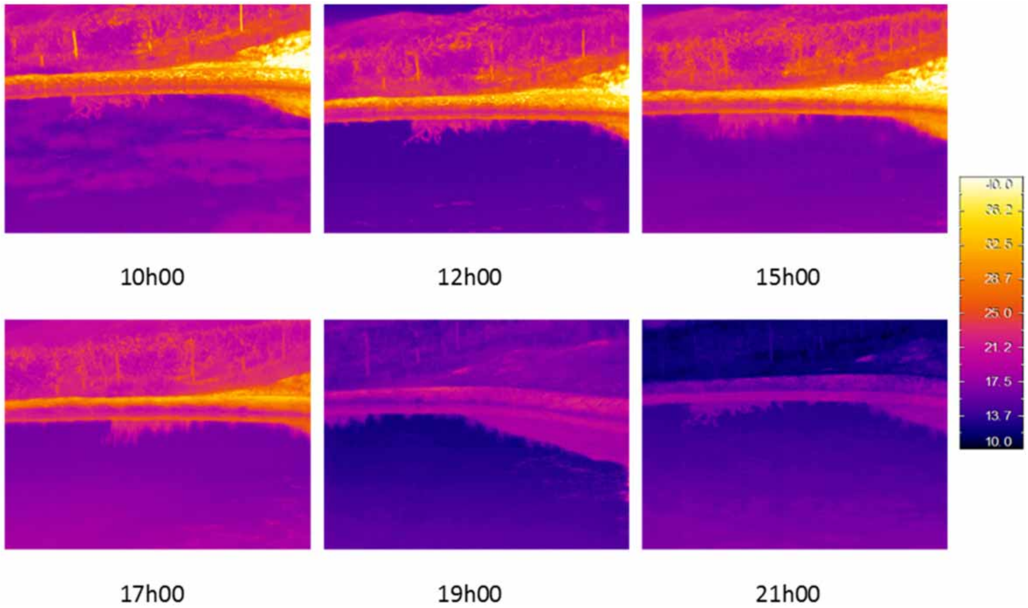

Figure 6 | Thermal images retrieved from site B – lake with no vegetation, at different periods of time (h).

areas of the water masses that show higher temperatures may be attributed in part to the reflection of radiation coming from the clouds and coming from the surroundings.

At site C, the lake partially vegetated with *L. minor* was analyzed and results are shown in Figure 7. As in the previous case, the temperature of the water mass is always inferior to the surrounding pavement, both when the water is in shadow (lower surface temperatures) or when it is under direct solar radiation (higher surface temperatures). On the contrary, the temperature of the water exposed to the sun is slightly higher than the temperature of the vineyard. That may be due to the thermal imaging being partly in shadow due to the effect of its own leafs. The temperature of the water mass in shadow is always lower than the temperature of the vineyard, except at 21 h.

Concerning the quantitative evaluation, Table 2 shows the measurements for surface temperatures at each site and moment (hour), having in consideration an average

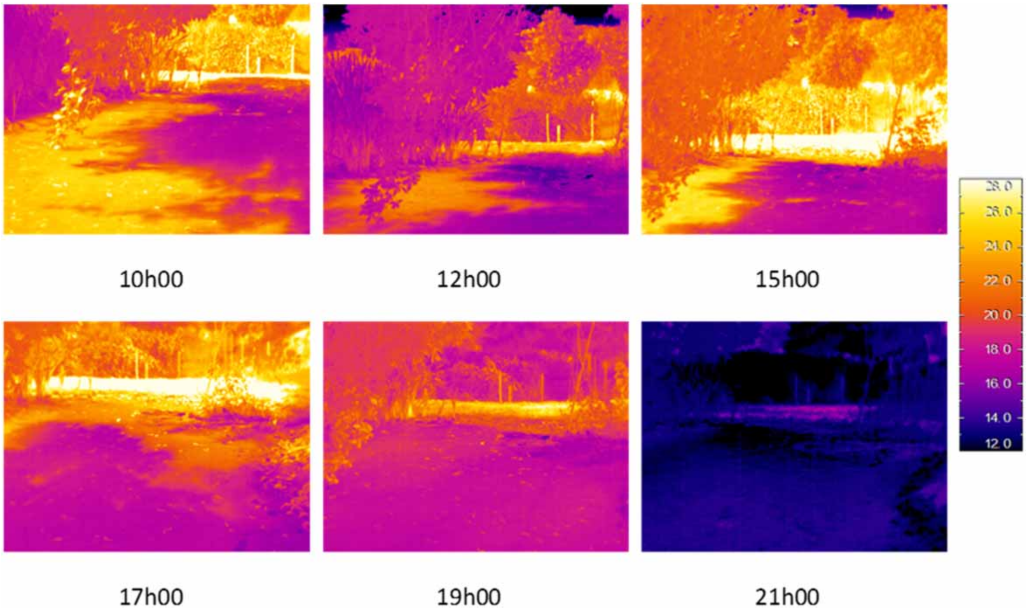

Figure 7 | Thermal images retrieved from site C – lake partially vegetated with *Lemna minor*, at different periods of time (h).

Table 2 | Surface temperature measurements (°C) for each site

Sites	10h00	12h00	15h00	17h00	19h00	21h00
Site A1						
Plants (sun)	19.1	20.6	20.3	23.3	–	–
Plants (shadow)	15.5	18.2	16.3	19.8	17.2	14.6
Soil	28.6	33.4	40.1	26.6	18	15.2
Site A2						
Plants	21.1	21.1	25.3	22.5	15.8	11.7
Wall	19.4	20.1	28.4	36.4	25.7	22.8
Site A3						
Plants (sun)	18.0	18.6	22.0	–	–	–
Plants (shadow)	15.5	18.1	19.4	21.8	20.0	15.1
Soil	19.0	20.2	39.5	36.0	21.2	15.0
Site B						
Water	16.7	15.5	16.8	16.8	13.4	13.4
Vineyard	19.9	19.7	20.4	20.7	15.9	12.4
Soil	35.2	33.9	35.2	29.3	16.8	11.3
Site C						
Water (sun)	24.6	21.2	25.8	21.9	19.2	–
Water (shadow)	17.4	16.2	16.7	17.7	17.6	13.5
Vineyard	23.7	18.7	24.8	21.1	18.5	11.1
Soil	32.9	25.7	35.9	32.8	24.3	15.4

Note: Site A1, A2, and A3: CW. Site B: lake with no vegetation, surrounded by a stone border, soil and at a distant plan vineyard. Site C: lake, partially vegetated with *Lemna*, surrounded by a stone pavement and in a second plan a vineyard.

value of similar areas for each site (30 × 30 pxl for thermal images obtained in site A and 10 × 10 pxl for thermal images obtained in sites B and C). In Figure 8 the differences between surface temperature (Table 2) and air temperature (Table 3) for each site and measurement moment, in different hours of the day, are presented.

It is possible to verify that the CW temperature is always inferior to the air temperature, being in general lower that air temperature between 5 and 10 °C, if at shadow, and between 0 and 5 °C, if at sun. The soil temperature is always higher than the air temperature, except in the cases when it is in shadow or at night. The soil temperature is also higher than the stone wall, which was expectable, since the period of time that direct solar radiation reaches the wall (vertical surface shaded by the surrounding vegetation) is inferior to the soil, lowering the heat absorption (short wave radiation) and the emissivity of the wall is superior to the soil, fact that enables the release of heat by long wave radiation. Differences in the temperature up to 22 °C, between CW canopy and the surrounding soil, were registered.

It is possible to verify that water in site B, which was exposed to solar radiation in all measurements, except between 19 h and 22 h, presents temperatures similar to those recorded in the shaded water in site C. This may be due to the fact that the water mass in site C has floating plants, which increases its temperature patterns, its behavior

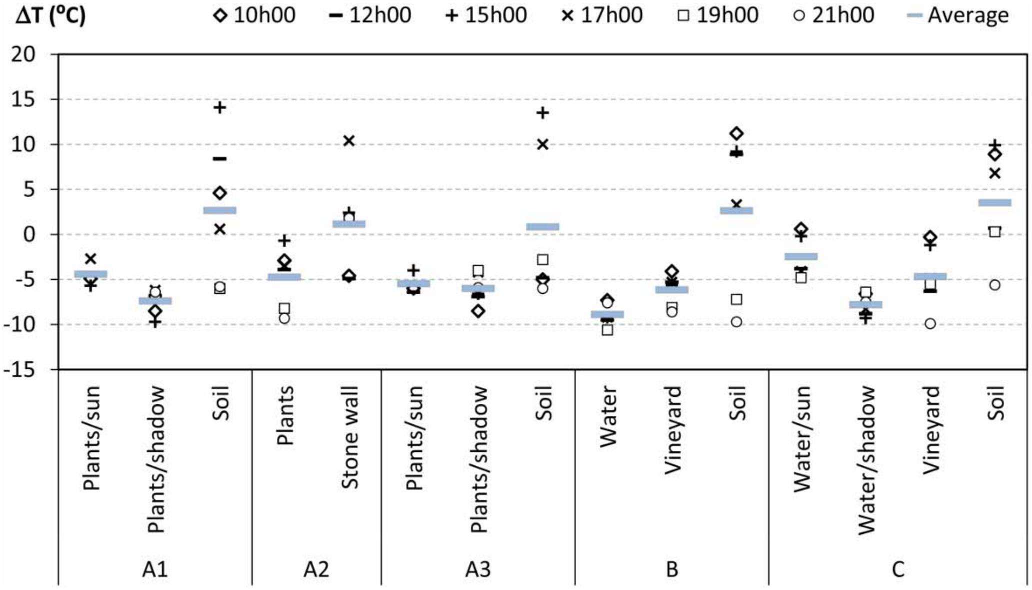

Figure 8 | Differences between surface temperature and air temperature for each site and element.

Table 3 | Outdoor climate conditions during the test campaign

		Time (hour)					
Climatic parameter	**Used devices**	**10:00 h**	**12:00 h**	**15:00 h**	**17:00 h**	**19:00 h**	**21:00 h**
Temperature (°C)	Pt100 sensor	24	25	26	26	24	21
Relative humidity (%)	Hygrometer sensor	64	60	56	57	61	63
Observation		Sunshine	Sunshine	Sunshine	Sunshine	Sunset	Night (some clouds)

becoming similar to that in the CW. For site B, differences in the temperature up to about 19 °C between the lake and the surrounding pavement were registered. For site C the differences in the temperature between the lake and the surrounding pavement were found to be up to about 15 °C.

Hill & Payton (2000) had studied the effect of plant fill ratio on water temperature, in a free-water-surface CW, comparing vegetated and non-vegetated systems. They came with the conclusion that, in general, systems without vegetation showed greater daily variation in temperature and were significantly warmer than vegetated cells. In general, the water masses (constructed lakes partially vegetated and non-vegetated) assured lower surface temperatures than the fully vegetated CW site, based mainly on diurnal patterns analysis. The influence of land use and land cover impacts to different extents the surrounding ambient temperature, being the temperature increase in urban areas associated to an expansion of non-vegetated areas (Nonomura *et al.* 2009). The role of green and blue infrastructures in climate change mitigation and adaptation has been highlighted by other authors, although further research is needed due to their multi-functional and multi-scale nature (Demuzere *et al.* 2014). In an urban context, the use of vegetation in aquatic compartments or others (such as green roofs) have a direct impact in the surrounding temperature and contribute to lowering, to a certain extent, the heat island effect (USEPA 2008; Razzaghmanesh *et al.* 2016). These issues are very important in terms of the environmental dimension but also concerning the human thermal responses (Xiong *et al.* 2015). The potential influence of these infrastructures in mitigating the heat island effect, due to the surface cover by vegetation, will need further investigation, however, the challenging innovative application of IRT has been proven.

Surface temperature comparison for three plant species

In order to evaluate the surface temperatures of different plants, three species were considered (Appendix S2 – see supplementary data, available with the online version of this paper): *Z. aethiopica*, *C. flaccida* and *C. indica*. It was taken into account, for the three plant species, the same emissivity (0.98) and the background temperature calibration was considered equal to 10.7 °C. The surface temperature acquired for each specie was in average 34.8 °C (22.5–42.8 °C) for *Z. aethiopica*, 34.6 °C (25.7–42.8 °C) for *C. flaccida* and 36.9 °C (26.1–52.4 °C) for *C. indica*. The *Z. aethiopica* and *C. flaccida* have similar temperatures, in contrast to *C. indica* that show higher temperatures (in average 2 °C). This could be attributed to the fact that the leaf color, slightly darker and reddish than the other two plants, may increase to a certain extent the absorption of solar radiation, leading to the increase of surface temperature. In this case, the color of the leaf was the determinant factor for the temperature range. This has shown that even plants from the same genus (*Canna*) have different impact on leaf surface temperatures. Although comparison between species should take into consideration the blossom time, plants' stomatal response, and thermoregulation capacity, since metabolic rate at different stages may vary according to plant parts (Lamprecht *et al.* 2002; Watling *et al.* 2008; Costa *et al.* 2013). Besides that, leaf temperature depends on factors such humidity, air temperature and incident radiation (Gómez-Bellot *et al.* 2015); however, in the present study, the three species were evaluated under the same conditions. The outcome of the comparison between the plants species undertaken in the present study could contribute to be a differentiating factor to have in consideration when selecting species for a CW.

To our knowledge, the comparisons presented in this study show a broader application of IRT, allowing us to infer about promoting the use of vegetation to lowering the surface temperature, with direct impact on the surrounding area. Other approaches may also be coupled with thermal imaging with several purposes (e.g. Lee *et al.* 2010; Jiménez-Bello *et al.* 2011).

Application of this technique to biosystems is thus promising in order to evaluate and consider other ecosystem services and further deepen the knowledge, since in a biosystem the role that each element plays is very important as the ecosystem services functions. This comes in agreement with the work done by Rozos *et al.* (2013) exploring the potential for the adoption of an integrated blue-green approach for urban areas management. In the end, these results would allow inference about these biosystems as tools for climate change mitigation and promote a positive environmental management.

CONCLUSIONS

The IRT technique allowed to study the influence of different elements in different biosystems, from the surface temperature of water to the vegetation, under the same conditions. This has enabled demonstration of the influence of each element within the biosystem and their contribution to the surrounding area. This approach has allowed us to evaluate the potentialities of this technique, applied to this field, and further research studies will intend to fully address the quantification of the impact of such structures.

The presence of plants and the water promoted, in general, the lowering of the surface temperatures when comparing to its surroundings (pavement or soil). The comparison of leaf surface temperatures between three plant species has shown that *C. indica* presents, on average, slightly higher surface temperatures when compared to *Z. aethiopica* and *C. flaccida*. We hypothesize that the color of the leaf had a higher impact on the surface temperatures independently of the species and genus.

The present study indicates that the inclusion of biosystems, such as lakes or CWs, in a site can represent a means of lowering superficial temperature influencing the surrounding environment, having to some extent impact on the heat island effect, and be used as tools for environmental management. It would also support a strategy of empowerment on the use of the biosystems as green and blue infrastructures.

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REFERENCES

Ballester, C., Jiménez-Bello, M. A., Castel, J. R. & Intrigliolo, D. S. 2013 Usefulness of thermography for plant water stress detection in citrus and persimmon trees. *Agricultural and Forest Meteorology* **168**, 120–129.

Barreira, E., Almeida, R. M. S. F. & Delgado, J. M. P. Q. 2016 Infrared thermography for assessing moisture related phenomena in building components. *Construction and Building Materials* **110**, 251–269.

Calheiros, C. S. C., Bessa, V. S., Mesquita, R. B. R., Brix, H., Rangel, A. O. S. S. & Castro, P. M. L. 2015 Constructed wetland with a polyculture of ornamental plants for wastewater treatment at a rural tourism facility. *Ecological Engineering* **79**, 1–7.

Chen, F., Kusaka, H., Bornstein, R., Ching, J., Grimmond, C. S. B., Grossman-Clarke, S., Loridan, T., Manning, K. W., Martilli, A., Miao, S., Sailor, D., Salamanca, F. P., Taha, H., Tewari, M., Wang, X., Wyszogrodzki, A. A. & Zhang, C. 2011 The integrated WRF/urban modelling system: development, evaluation, and applications to urban environmental problems. *International Journal of Climatology* **31** (2), 273–288.

Costa, J. M., Grant, O. M. & Chaves, M. M. 2013 Thermography to explore plant-environment interactions. *Journal of Experimental Botany* **64** (13), 3937–3949.

Demuzere, M., Orru, K., Heidrich, O., Olazabal, E., Geneletti, D., Orru, H., Bhave, A. G., Mittal, N., Feliu, E. & Faehnle, M. 2014 Mitigating and adapting to climate change: multi-functional and multi-scale assessment of green urban infrastructure. *Journal of Environmental Management* **146**, 107–115.

Freitas, S. S., Freitas, V. P. & Barreira, E. 2014 Detection of façade plaster detachments using infrared thermography – A nondestructive technique. *Construction and Building Materials* **70**, 80–87.

Gómez-Bellot, M. J., Nortes, P. A., Sánchez-Blanco, M. J. & Ortuño, M. F. 2015 Sensitivity of thermal imaging and infrared thermometry to detect water status changes in Euonymus japonica plants irrigated with saline reclaimed water. *Biosystems Engineering* **133**, 21–32.

Hill, D. T. & Payton, J. D. 2000 Effect of plant fill ratio on water temperature in constructed wetlands. *Bioresource Technology* **71**, 283–289.

Jiménez-Bello, M. A., Ballester, C., Castel, J. R. & Intrigliolo, D. S. 2011 Development and validation of an automatic thermal imaging process for assessing plant water status. *Agricultural Water Management* **98**, 1497–1504.

Jones, H. G., Archer, N., Rotenberg, E. & Casa, R. 2003 Radiation measurement for plant ecophysiology. *Journal of Experimental Botany* **54** (384), 879–889.

Jones, H. G., Serraj, R., Loveys, B. R., Xiong, L., Wheaton, A. & Price, A. H. 2009 Thermal infrared imaging of crop canopies for the remote diagnosis and quantification of plant responses to water stress in the field. *Functional Plant Biology* **36**, 978–989.

Karczmarczyk, A. & Baryła, A. 2013 Cold season temperature pattern over a horizontal subsurface flow constructed wetland – application of thermography in environmental research. *Fresenius Environmental Bulletin* **22** (12a), 3694–3699.

Lamprecht, I., Schmolz, E., Hilsberg, S. & Schlegel, S. 2002 A tropical water lily with strong thermogenic behavior-thermometric and thermographic investigations on *Victoria cruziana*. *Thermochimica Acta* **382**, 199–210.

Lee, W. S., Alchanatis, V., Yang, C., Hirafuji, M., Moshou, D. & Li, L. 2010 Sensing technologies for precision specialty crop production. *Computers and Electronics in Agriculture* **74**, 2–33.

MA – Millennium Ecosystem Assessment 2005 *Ecosystems and Human Well-Being: Synthesis.* Island Press, Washington, DC, USA.

Nonomura, A., Kitahara, M. & Masuda, T. 2009 Impact of land use and land cover changes on the ambient temperature in a middle scale city, Takamatsu, in Southwest Japan. *Journal of Environmental Management* **90** (11), 3297–3304.

Omega 1998 *Transactions in Measurement & Control – Volume 1 – Non Contact Temperature Measurement*. Putnam Publishing Company and OMEGA Press LLC, New York, NY, USA.

Razzaghmanesh, M., Beecham, S. & Salemi, T. 2016 The role of green roofs in mitigating Urban Heat Island effects in the metropolitan area of Adelaide, South Australia. *Urban Forestry & Urban Greening* **15**, 89–102.

Rozos, E., Makropoulos, C. & Maksimovic, Č. 2013 Rethinking urban areas: an example of an integrated blue-green approach. *Water Science & Technology: Water Supply* **13** (6), 1534–1542.

Schallenberg, M., de Winton, M. D., Verburg, P., Kelly, D. J., Hamill, K. D. & Hamilton, D. P. 2013 Ecosystem services of lakes. In: *Ecosystem Services in New Zealand – Conditions and Trends* (J. R. Dymond, ed.). Manaaki Whenua Press, Lincoln, New Zealand.

Schuetz, T., Weiler, M., Lange, J. & Stoelzle, M. 2012 Two-dimensional assessment of solute transport in shallow waters with thermal imaging and heated water. *Advances in Water Resources* **43**, 67–75.

USEPA – United States Environmental Protection Agency 2008 *Reducing Urban Heat Islands: Compendium of Strategies.* US Environmental Protection Agency, Washington, DC, USA.

Watling, J. R., Grant, N. M., Miller, R. E. & Robinson, S. A. 2008 Mechanisms of thermoregulation in plants. *Plant Signal Behav.* **3** (8), 595–597.

Xiong, J., Lian, Z., Zhou, X., You, J. & Lin, Y. 2015 Effects of temperature steps on human health and thermal comfort. *Building and Environment* **94**, 144–154.

Yang, W., Chang, J., Xu, B., Peng, C. & Ge, Y. 2008 Ecosystem service value assessment for constructed wetlands: a case study in Hangzhou, China. *Ecological Economics* **68**, 116–125.

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