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Identifying design shortcomings and heat-island effects in schools located in warm climates: An outdoor environmental assessment procedure based on remote sensing tools.

Abstract

The current effects of global warming and a growing obsolescence in the built environment are rendering outdoor areas of existing schools thermally vulnerable and uncomfortable, thereby causing unsuitably hot temperatures during the academic year. This paper aims to diagnose and reveal the main weaknesses and design shortcomings in outdoor areas of schools. To this end, this research contributes with a normalised characterisation procedure ~~is incorporated~~ that provides quantified parameters that not only focuses on design patterns and wooded and shaded spaces (Normalised Difference Vegetation Index), but also on ground materials (Solar Reflectance Index) in order to reduce the impact of solar radiation and adjust future renovation strategies for southern European schools. ~~By~~With the novelty of using remote sensing tools and in situ measurements, an outdoor environmental assessment is made of a representative sample of 100 schools in Andalusia, a Mediterranean region in southern Spain. The results demonstrate that shade percentages are greatly limited, whereby 90% of schools contain between 0 to 10% of wooded area, mostly with a vegetation index in the range of 0 to 0.3, along with 70% of centres with more than 80% of their ground area covered with hard paving, thereby involving a higher absorption of solar energy. Conclusions not only identify weaknesses and design shortcomings and highlight key implications based on the promotion of heat mitigation strategies through bioclimatic renovation actions, but they also provide ranges of recommended values for the established indices, towards achieving more shaded and comfortable areas in schools.

Keywords

Heat-island Mitigation Strategies; Mediterranean Schools; Normalised Difference Vegetation Index; Outdoor Environmental Analysis; Remote Sensing Tools; Solar Reflection Index.

1. Introduction

In both the "New Urban Agenda" [1] and the "World Cities Report" [2], the United Nations highlights the importance of addressing urban regeneration strategies in an eco-efficient and sustainable way as one of the main challenges of the 21st century [3]. The growth and expansion of cities throughout the 20th century have led urban reports to focus on the obsolescence and ageing process of existing buildings, and to state that more than 40% of the European building stock is over 50 years old [3,4]. Hence, the European guidelines for the adaptation and renovation of the built environment have been put in place to meet the current comfort, energy, and climatic requirements and to achieve a sustainable urban transition [5,6] by opting for bioclimatic conditioning techniques in every region with warm temperatures [7].

Schools represent a significant proportion of the building sector, and constitute approximately 18% of all non-residential buildings in Europe; these buildings are also undergoing an ageing and deterioration process, since more than 50% of the educational centres that currently exist in Europe were built before 1990; this figure is even higher (60%) in southern Mediterranean countries [4,8]. Most of the existing schools in warm regions are becoming obsolete with respect to the sustainable design patterns currently in force, which makes them uncomfortable spaces under the global warming scenario, and hence the majority of existing schools require outdoor and indoor action proposals at different levels [9,10]. In order to promote feasible and effective strategies [11], these arguments justify the need to carry out research studies in representative schools with normalised procedures to diagnose their design patterns, conservation status, and indoor/outdoor environmental quality [12,13].

The geographical location of Andalusia, the southernmost region in Spain, and its Mediterranean climate make this area particularly sensitive and vulnerable to global warming, with an average overall temperature increase of 2.3ºC in the last 25 years. On certain days of overheating stress, maximum temperatures between 35-45ºC in the hottest months of the year [14] affect the concentration, comfort, and efficiency of education in early autumn, spring, and summer, which overlap significantly with the academic year [15]. Under these premises, a new specific law has been launched in this region to improve the thermal and environmental conditions of schools through bioclimatic techniques [16]. This demonstrates the need to carry out this research study in order to detect influential environmental patterns and to quantify certain parameters in school playgrounds under extremely hot temperatures, for their potential replication in other Mediterranean locations.

This research aims to establish and display an assessment protocol of the main outdoor environmental parameters in school playgrounds by assessing shade and solar reflectance indices that entail an innovative approach based on the use of remote sensing tools. The newly incorporated procedure enables weaknesses to be identified and design shortcomings to be demonstrated that commonly exist in outdoor spaces of schools located in warm climates. These weaknesses and shortcomings are mainly related to the lack of vegetation and shaded areas, and to unsuitable ground materials, whose impact can increase the heat-island effects and negatively influence the comfort and the academic performance of the educational community.

This work provides an outdoor environmental analysis of a representative sample of 100 public schools from the Andalusian region, which includes both primary and secondary schools [17], for the characterisation and quantification of parameters related to architectural composition, outdoor surface ratios, vegetation and shaded spaces (Normalised Difference Vegetation Index (NDVI)), and to paving materials (Solar Reflectance Index (SRI)). This analysis provides information so that an informed selection can be made regarding which bioclimatic techniques should be considered in future renovation strategies to improve the outdoor environmental quality in southern European schools. The data, obtained through in situ measurements and remote sensing tools, is expected to serve towards the adjustment of the outdoor design patterns of schools and their inclusion in future renovation guidelines by incorporating shaded areas and bioclimatic features in paving materials that ensure thermal and environmental comfort in open areas of schools.

The following section presents a literature review of related research in order to demonstrate the usefulness and novelty of this study. This study is structured to then define the scope of application, the school sample, and the data collection procedure carried out using remote sensing tools. Subsequently, the main data obtained for each school is displayed in tables and graphs, which enables the principal representative patterns in a warm location to be discussed and major conclusions to be drawn that promote bioclimatic actions, thereby enhancing the importance of shade, vegetation, and ground materials in the reduction of the impact of global warming in schools.

2. Literature review

Recent work has highlighted the usefulness of studying environmental performance in the school sector, and is largely focused on quantifying and improving indoor environmental quality and energy performance [18]. Gil-Baez et al. [19] incorporate a set of low-cost passive refurbishment solutions for the building envelope of Mediterranean schools, as an opportunity to potentially improve their energy performance. Trompetter et al. [20] demonstrate, under various ventilation scenarios, the need to limit exposure to dust in schools through mitigation strategies, and they highlight the key role of ventilation in schools in guaranteeing the students' well-being, which has achieved greater recognition under the current health crisis due to the COVID 19 pandemic [21]. Heracleous and Michael [22] demonstrate the benefits of natural ventilation in terms of thermal comfort and overheating risk for schools in the Mediterranean region. Lastly, Lizana et al. [23] provide an innovative energy modelling process for the evaluation of the real energy performance of schools and of potential energy savings in a warm Mediterranean context.

However, only a few studies focus on the improvement of comfort and well-being in outdoor areas of schools, which is especially important in warm regions where climatic conditions are continually worsening due to global warming, for which new heat mitigation strategies are required [24,25]. It is important to refer to the contributions provided by Abdallah et al. [26], which, through survey indicators, quantified the impact on students of various shading strategies; their results indicated a recommendation for an increase in greenery and tree density in order to reduce heat stress for students in school playgrounds. Additionally, Yang [27] demonstrated the benefits that trees introduce in open areas where improvements in outdoor thermal comfort are required, and provided a database for the selection of a variety of vegetation species for the summer months as straightforward advice for architects and developers.

Regarding paving materials, several studies quantify the impact of different ground surfaces in the thermal environment: Huang et al. [28] provided evidence of the significant effect of the reflectivity of the selected material on surface temperature in summer months; and Taleghani [29] compared the albedo value of various surfaces and showed that very high or very low albedo values can indicate thermal discomfort of pedestrians in urban open spaces. Finally, as a demonstration of the importance of studying the microclimatic performance of schools, studies developed by Khledj and Bencheikh [30] and Aghamolaei et al. [31] incorporated numerical and simulation tools to achieve thermal comfort in indoor and outdoor spaces corresponding to a hot and dry climate.

Additionally, Table 1 provides a brief summary of the particular studies that have incorporated significant insights and striking interventions in the various research subtopics that have influenced the design of this research, such as the use of remote sensing tools, outdoor environmental assessment, and the promotion of heat mitigation strategies against global warming.

Table 1. Contributions, findings, and/or gaps in particular research subtopics related to this study

Subtopic	Research study	Contributions and/or gaps
Outdoor environmental assessment – Heat mitigation strategies	Mohamed et al. (2021) [32]	· Assess the impact of a passive wall for improving thermal conditions in schools. · Highlight the lack of adequate design of outdoor areas in schools in hot climates.
	Kenawy et al. (2021) [33]	· Enhance sustainable outdoor areas with comfortable conditions in summer. · Analyse 4 thermal comfort measures: Neutral, preferred, acceptable, & comfort.
	Kükrer & Eskin (2021) [34]	· State that thermal conditions are significant factors in academic performance. · A more combined indoor/outdoor approach to thermal analysis is lacking.
	Xue et al. (2021) [35]	· Increased attention to outdoor thermal comfort is getting crucial in urbanisation. · Aim to renovate and improve thermal comfort at the pedestrian level.

Remote sensing models	Song et al. (2020) [36]	·State the suitability of remote sensing for the quantification of ground radiation. ·Indicate the useful connection between remote sensing and social sensing.
	Zhu et al. (2019) [37]	. Highlight remote sensing contributions for urban areas from multiple studies. . Indicate the need for urban data and remote sensing scientists to work together.
	Vanos et al. (2016) [38]	·Provide a remote sensing quantification of surface temperatures in playgrounds. ·State that shading strategies are the most promising heat mitigation techniques.

Although all the aforementioned studies have generated significant findings in their independent research fields, there is a research gap in particular studies that focus on analysing the performance of open areas of schools located in hot climates. This study therefore incorporates a new approach by quantifying determining parameters related to wooded area, ground surfaces, and other architectural patterns in order to improve the environmental comfort for students in school playgrounds. Thus, this paper fills this knowledge gap by incorporating an outdoor environmental assessment procedure in existing schools, combining in situ measures from technical visits along with the use of remote sensing tools. This assessment protocol is tested and applied to a representative sample of 100 schools located in Andalusia, a Mediterranean region in southern Spain (Subsection 3.1.). Here, distribution schemes and open surface ratios are obtained, along with the assessment of normalised parameters on vegetation, shade, and solar reflection of the ground in order to identify common patterns, mean deviations, and design breaches that contribute towards the incorporation of bioclimatic strategies via heat-island mitigation guidelines.

3. Methodology

Figure 1 represents a flowchart that shows the main phases, which entail the background, the scope of application, and the procedure to obtain data and results from the chosen parameters in order to fulfil the aims of the research. The methodology of the study focuses on obtaining technical and analytical information from the outdoor spaces of schools located in southern Europe, based on technical in situ measurements and using remote sensing tools in an effort to determine the influence and correlation between certain parameters in order to carry out bioclimatic actions that reduce the effects of overheating on students during the hottest months. The procedure for obtaining the data is structured into 3 categories: (A) Design composition and thermal parameters; (B) Shaded surface measurements and NDVI values; and (C) Ground materials and SRI values. The following subsections define the criteria determined for the selected case studies together with the data collection.

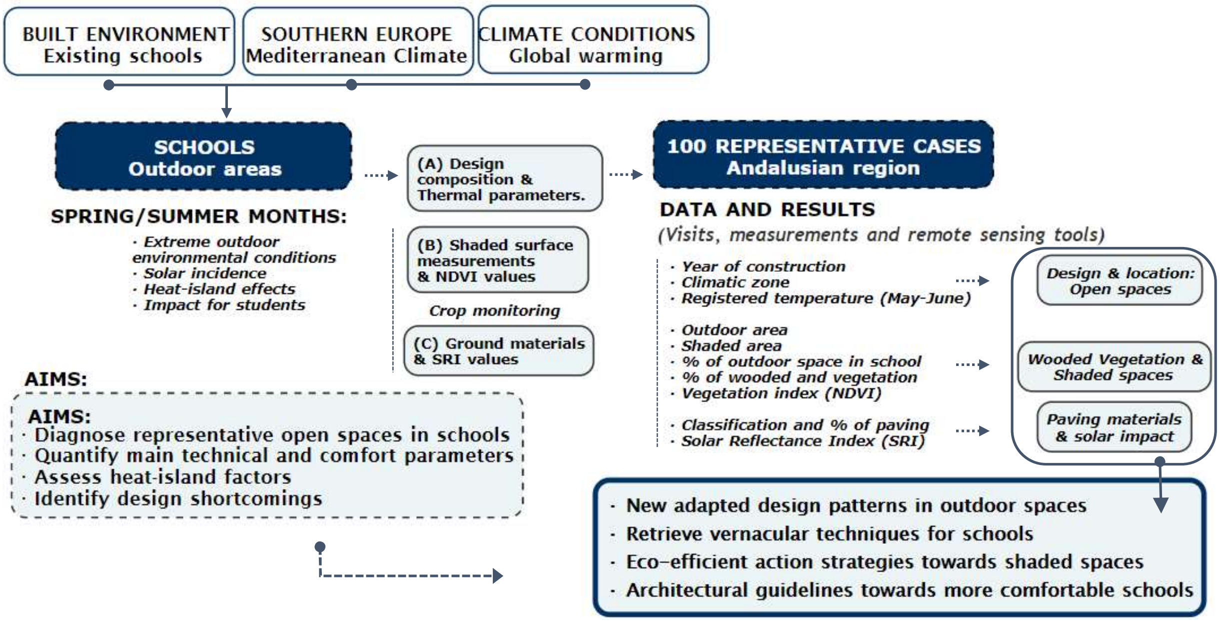

Figure 1. General outline of the aims and research procedure

3.1. Scope of application. Case studies

The scope of the study incorporates a representative selection of educational centres from southern Spain, and addresses primary and secondary schools. The criteria dictates that these schools must be located in the major municipalities of the region with more than 10,000 inhabitants, that they were built in the second half of the 20th century and/or have more than 10 years of use, correspond to different design patterns that commonly present a predominant outdoor space, and belong to warm climatic subzones in the Andalusian region where the maximum temperatures reached in the summer in the outdoor environment exceed 30ºC before midday. Under these criteria, 100 public schools are selected, 50 primary and 50 secondary schools, belonging to 50 municipalities, thereby additionally allowing the outdoor environmental performance between primary and secondary schools to be compared in terms of the age of the students, the different architectural typologies, and also the effectiveness of the management carried out by municipalities and the regional government, respectively. This representative sample yields significant results and conclusions based on common design patterns and adjusted action strategies that could be replicated in outdoor spaces of schools located in other Mediterranean countries, and those located in other warm climatic zones affected by global warming.

Figure 2 presents the location in the Andalusian region of the 50 cities and municipalities where both a primary and a secondary school have been studied. The selection of these schools, spread all across the region under different climatic zones [39], aims to bring together the representativeness of this region from southern Europe. The main focus is on a warmer area corresponding to the valley of the main river that crosses this region, where the average temperatures in June, July, and September frequently exceed 30ºC or even 35ºC in the morning hours, and where the solar radiation is the highest in all of Spain, exceeding 18MJ/m^2 per day [40,41].

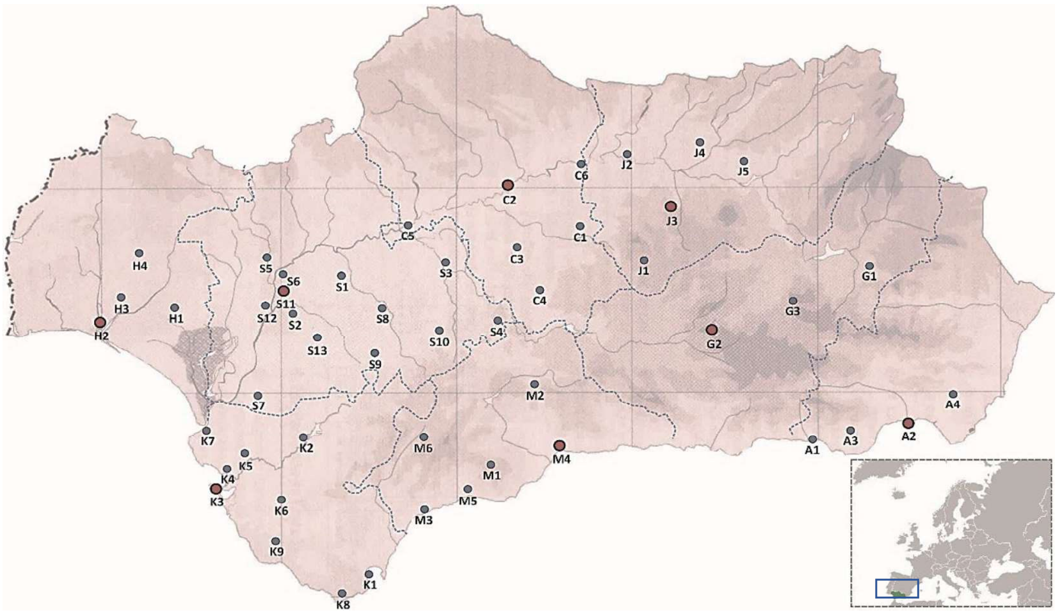

Figure 2. Acronyms of the selected schools in the Andalusian region (Lat.:N37º36’0’’; Long.:W4º;30’0’’).

Finally, each school has been assigned an acronym in accordance with its province (A=Almeria, K=Cadiz, C=Cordoba, G=Granada, H=Huelva, J=Jaen, M=Malaga, S=Seville) and a prefix that corresponds to whether it is a primary (P) or secondary (S) school, in order to maintain the anonymity of the centres in the manuscript. The full list of school names and municipalities are available as supplementary data (Appendix I) of this paper.

3.2. Data collection and monitoring campaign

The starting information, data collection, and results for each selected primary or secondary school has been structured into three main subsections: (1) Design composition and thermal location of the school’s outdoor space; (2) Shaded surface measurement and ratio together with the NDVI; and (3) Identification of ground materials and their average Solar Reflectance Index (SRI).

Firstly, historical, graphical, and compositional information has been gathered from each school in order to consider the year of construction and to carry out measurements on the current planimetry scale [42]. Furthermore, climatic zones have also been defined based on the thermal classification provided by Spanish legislation, as well as average temperatures recorded during May and June (hottest months of the Spanish academic year) at 11:00 a.m., when outdoor spaces of the school are in full use by students during their morning break [39,40].

Secondly, regarding vegetation and shaded spaces, the wooded area and the corresponding ratio in the outdoor space of each school have been measured by using aerial images along with remote sensing tools (Landsat and especially the Crop Monitoring tool based on data provided by the Sentinel-2 satellite) during May and June, 2020, at 11:00 a.m. Furthermore, vegetation maps and mean values have been provided through the NDVI, obtained by using the Crop Monitoring remote sensing tool with a 0.25-0.5m resolution [43], after having introduced the perimeter of the plot and having obtained the average value and the detailed map of values presented in Figures 6 and 7.

The NDVI offers information on the distribution and type of vegetation in a given plot and is calculated according to the equation [$eq.$:1], where μ_{nir} and μ_{red} are multispectral reflectance values of the near infrared band and the red band respectively, and combines images obtained by the Sentinel 2-L2A and Sentinel 2-L1C satellites [44]. The NDVI frequently takes values of between 0 and 0.3 when vegetation is scarce or null, and values higher than 0.3 when the presence of vegetation is indicated, while values approaching 1 indicate thick foliage [45].

$$NDVI = \frac{\mu_{nir}-\mu_{red}}{\mu_{nir}+\mu_{red}} \quad [eq.:1]$$

Thirdly, a classification of outdoor paving materials has also been carried out into three main groups: (1) Hard (H) (e.g., concrete, cement slabs, and tiles); (2) Earthen (E) (e.g., sand and soil); and (3) Green (G) (e.g., gardens, grass, and lawn). This classification enables the quantification of the percentage of surface occupied by each family of materials. Furthermore, in order to study the impact of the solar incidence and the rebound of these materials on the heat-island effect generated in outdoor spaces [46,47], mean values of the Solar Reflectance Index (SRI) have been determined for each school.

The SRI is a single indicator of the solar reflectance and emissivity of materials that represents the ability to reflect solar heat thereby mitigating the temperature increase of a flat opaque material exposed to the sun. Crop monitoring simulation of this SRI parameter is obtained by introducing the plot, the characterisation of the soil, and the reflected spectrum of the materials in the remote sensing tool through the Sentinel-2 satellite. The range of values lies between 0 (standard black) and 1 (standard white), and therefore the lower the SRI value, the hotter a material is likely to become in direct sunlight. The SRI value is obtained according to the expression [$eq.$:2], where T_s (K) is the temperature that the considered surface would steadily reach when irradiated by a reference solar flux $Isol_{max}$=1000W/m^2 at normalised atmospheric air temperature T_{air}=310K and sky temperature T_{sky}=300K, while T_b (K) and T_w (K) are temperatures that would be steadily reached by the black reference surface (b=0.05) and by the white reference surface (w=0.80), respectively [48].

$$SRI = \frac{T_b-T_s}{T_b-T_w} \quad [eq.:2]$$

For this research, the SRI can be considered to be the most suitable indicator for the assessment of the response of paving materials to solar radiation, since the albedo or "whiteness" of a surface is a simple ratio of reflected to incident radiation and fails to take emissivity into account: this factor is crucial for the proper measurement of the heat-island effect. Given the mixture of materials in each school playground, an average SRI value has been determined for the entire space, which has been computed by interpolating between the values obtained for each material and the black and white reference values.

4. Results and discussion

The main results obtained are described in Tables 2 and 3, which correspond to Primary (P) schools and Secondary (S) schools respectively, and are ordered according to the eight provinces of the region. Each table organises the information of each school and provides the year of construction, the corresponding climatic zone, and the maximum temperature recorded in May and June. Furthermore, a second group of results defines multiple parameters on surfaces and shading ratios and the NDVI index related to the wooded area, while the classification of ground materials and the mean SRI reflectance factor are defined in the last columns.

Each table shows a comprehensive view of the set of results that leads to a detailed and interrelated analysis of the parameters obtained for each school. The characterisation and location of the schools demonstrate the representativeness of the selected sample explained in subsection 3.1., with 60% built before 2000, and the majority of case studies exceeding 20 or 30 years of service, with the oldest school dating back to 1920 (S-S10) and the most modern to only 2015 (S-S5). Additionally, more than 70% of the schools are located in the hottest climatic zones of Spain according to Spanish legislation (A3, A4, and B4), with several schools located in mountainous areas with cooler climates (C3 and D3), and temperate coastal areas (B3-C4), which differentiates the performance of outdoor spaces in different climatic zones. Lastly, the maximum temperatures reached in each location are high values, far outside the comfort range, and an average maximum temperature of all schools of 36.1ºC is obtained, with an absolute maximum reached in one school of 42.5ºC (P-J1) and a minimum value of 28.3ºC (P-M6), to which must be added the high solar incidence that in certain locations exceeds 5.0 kWh/m^2.

Regarding the school composition and design, the outdoor surface and the percentage it represents with respect to the plot are generally established at approximately 70% of the plot area, which demonstrates the importance of these spaces in educational precincts. The values show a wide variety of scales in the selected cases, ranging from schools with large areas with more than 10,000m^2 of outdoor space and a great predominance over the building area (in many cases exceeding 85% of the total space of the plot) to other more urbanised schools, where the size of the plot is very limited and the outdoor space represents only 50% of the total area.

Table 2. Main results of primary schools regarding outdoor space, vegetation, and paving.

School - Location				Outdoor space - Shade - Vegetation					Paving-SRI	
Case	Year of constr.	Climatic Zone	Tª max.11h *(May-June)*	Outdoor area *(m^2)*	Shaded area *(m^2)*	% outdoor /plot	% shade /outdoor	NDVI *(0-1)*	% Paving *(H | E | G)*	SRI *(0-1)*
P-A1	1979	A4	34.8	10,409	880	74.1	8.5	0.07	100 | 0 | 0	0.35
P-A2	2007	A4	35.0	5,475	38	70.5	0.7	0.04	100 | 0 | 0	0.55
P-A3	2006	A4	35.8	8,768	380	73.1	4.3	0.18	50 | 30 | 20	0.55
P-A4	2009	B3	35.8	4,981	365	73.1	7.3	0.13	90 | 10 | 0	0.40
P-K1	2009	A3	31.1	5,124	155	67.2	3.0	0.19	60 | 35 | 5	0.50
P-K2	1971	B3	34.9	2,930	202	73.5	6.9	0.16	95 | 0 | 5	0.45
P-K3	1970	A3	37.5	3,024	5	67.0	0.2	0.18	100 | 0 | 0	0.45
P-K4	2008	A3	37.5	2,750	95	54.5	3.5	0.16	80 | 0 | 20	0.45
P-K5	1965	A3	37.2	5,143	234	69.8	4.5	0.14	95 | 5 | 0	0.45
P-K6	1960	B3	34.4	2,445	55	75.9	2.2	0.10	100 | 0 | 0	0.35
P-K7	1970	A3	39.0	2,906	235	66.8	8.1	0.10	90 | 0 | 10	0.45
P-K8	1982	A3	31.2	5,283	168	80.4	3.2	0.17	80 | 20 | 0	0.40
P-K9	1972	B3	32.3	3,045	115	63.8	3.8	0.07	100 | 0 | 0	0.35
P-C1	1980	C4	39.0	7,539	678	77.1	9.0	0.19	100 | 0 | 0	0.40
P-C2	1976	B4	41.2	9,241	442	78.9	4.8	0.19	60 | 40 | 0	0.45
P-C3	1950	C4	35.6	5,004	305	76.7	6.1	0.10	100 | 0 | 0	0.40
P-C4	1975	C4	38.6	8,004	345	79.1	4.3	0.18	30 | 70 | 0	0.60
P-C5	1970	B4	40.4	7,398	515	73.2	7.0	0.26	70 | 20 | 10	0.55
P-C6	1940	B4	41.5	5,856	183	75.1	3.1	0.17	100 | 0 | 0	0.45
P-G1	1969	D3	31.3	3,594	107	78.2	3.0	0.19	100 | 0 | 0	0.50
P-G2	1975	C3	35.2	8,516	586	81.3	6.9	0.20	90 | 10 | 0	0.50
P-G3	2000	D3	32.8	3,087	362	69.7	11.7	0.19	90 | 10 | 0	0.45
P-H1	1983	B4	39.9	8,402	312	86.1	3.7	0.16	60 | 35 | 5	0.45
P-H2	1987	A4	40.4	4,664	349	66.2	7.5	0.19	80 | 20 | 0	0.55
P-H3	2011	A4	40.6	3,275	134	54.6	4.1	0.16	90 | 10 | 0	0.45
P-H4	1980	B3	39.6	7,883	380	87.2	4.8	0.20	95 | 0 | 5	0.45
P-J1	1977	D3	34.2	9,277	245	79.9	2.6	0.16	100 | 0 | 0	0.25
P-J2	1970	C4	42.5	2,047	65	64.1	3.2	0.13	100 | 0 | 0	0.50
P-J3	2009	C4	41.1	7,681	128	72.9	1.7	0.15	70 | 30 | 0	0.60
P-J4	1970	C4	41.0	1,901	58	50.7	3.1	0.12	100 | 0 | 0	0.30
P-J5	1970	C4	38.3	11,3352	820	89.7	7.2	0.36	20 | 80 | 0	0.55
P-M1	1981	B3	33.2	7,042	382	79.6	5.4	0.21	100 | 0 | 0	0.50
P-M2	1980	C3	34.0	10,883	623	83.2	5.7	0.25	90 | 10 | 0	0.35
P-M3	2012	A3	33.0	4,102	20	68.4	0.5	0.19	100 | 0 | 0	0.55
P-M4	1986	A3	35.6	7,696	676	78.5	8.8	0.22	50 | 30 | 20	0.50
P-M5	1976	A3	31.0	6,562	765	74.8	11.7	0.30	70 | 0 | 30	0.55
P-M6	1960	D3	28.3	2,482	148	53.1	6.0	0.13	100 | 0 | 0	0.30
P-S1	1983	C4	39.2	8,432	823	88.4	9.8	0.17	30 | 70 | 0	0.50
P-S2	1983	B4	39.7	7,599	194	78.2	2.6	0.16	30 | 70 | 0	0.55
P-S3	2013	B4	38.6	5,320	112	74.9	2.1	0.12	40 | 60 | 0	0.60
P-S4	1998	C4	33.7	11,552	251	82.3	2.2	0.20	40 | 60 | 0	0.55
P-S5	1979	B4	41.6	14,436	215	77.0	1.5	0.14	30 | 70 | 0	0.55
P-S6	1990	B4	40.6	7,260	348	72.3	4.8	0.17	20 | 80 | 0	0.60
P-S7	2008	B4	37.9	3,853	138	86.4	3.6	0.14	100 | 0 | 0	0.40
P-S8	1975	B4	37.4	14,634	325	89.5	2.2	0.17	50 | 50 | 0	0.55
P-S9	1972	C4	35.5	8,227	271	75.3	3.3	0.19	100 | 0 | 0	0.45
P-S10	1920	C4	35.3	13,869	791	85.6	5.7	0.22	60 | 40 | 0	0.50
P-S11	1964	B4	40.2	3,405	162	52.3	4.8	0.12	100 | 0 | 0	0.45
P-S12	2008	B4	40.0	4,707	106	66.1	2.3	0.10	100 | 0 | 0	0.50
P-S13	1970	B4	38.5	4,165	88	76.0	2.1	0.12	100 | 0 | 0	0.50

Table 3. Main results of secondary schools regarding outdoor space, vegetation, and paving.

School - Location				Outdoor space - Shade - Vegetation					Paving - SRI	
Case	Year of constr.	Climatic Zone	Tª max.11h *(May-June)*	Outdoor area *(m^2)*	Shaded area *(m^2)*	% outdoor /plot	% shade /outdoor	NDVI *(0-1)*	% Paving *(H | E | G)*	SRI *(0-1)*
S-A1	1979	A4	34.8	7,200	228	77.5	3.2	0.08	90 | 0 | 10	0.35
S-A2	1998	A4	35.0	7,005	478	77.7	6.8	0.13	50 | 50 | 0	0.40
S-A3	1978	A4	35.8	7,398	178	73.1	2.4	0.13	90 | 10 | 0	0.45
S-A4	2009	B3	35.8	8,059	125	76.5	1.6	0.09	80 | 20 | 0	0.30
S-K1	1980	A3	31.1	7,282	171	80.9	2.3	0.16	90 | 10 | 0	0.45
S-K2	1981	B3	34.9	11,092	808	78.6	7.3	0.33	40 | 40 | 20	0.35
S-K3	2005	A3	37.5	4,359	130	50.2	3.0	0.11	90 | 10 | 0	0.55
S-K4	1993	A3	37.5	6,188	155	71.1	2.5	0.16	100 | 0 | 0	0.40
S-K5	1968	A3	37.2	8,082	354	80.8	4.4	0.15	60 | 40 | 0	0.50
S-K6	2000	B3	34.4	13,974	842	86.8	6.0	0.33	80 | 20 | 0	0.35
S-K7	1987	A3	39.0	9,948	271	81.7	2.7	0.24	40 | 60 | 0	0.50
S-K8	1970	A3	31.1	6,009	55	62.7	0.9	0.15	100 | 0 | 0	0.45
S-K9	1978	B3	32.3	9,157	488	72.7	5.3	0.28	20 | 80 | 0	0.30
S-C1	2008	C4	39.0	5,160	116	51.0	2.2	0.12	70 | 30 | 0	0.45
S-C2	2005	B4	41.2	8,226	230	73.2	2.8	0.13	90 | 10 | 0	0.40
S-C3	2011	C4	35.6	9,038	109	74.4	1.2	0.08	90 | 10 | 0	0.40
S-C4	2014	C4	39.2	10,188	315	67.2	3.1	0.12	70 | 30 | 0	0.45
S-C5	2010	B4	40.4	4,653	256	50.1	5.5	0.14	100 | 0 | 0	0.40
S-C6	1966	B4	41.5	5,890	148	75.9	2.5	0.26	100 | 0 | 0	0.45
S-G1	2003	D3	31.3	9,620	490	80.6	5.1	0.07	60 | 40 | 0	0.45
S-G2	1984	C3	35.0	6,936	346	76.7	5.0	0.25	90 | 10 | 0	0.50
S-G3	1968	D3	32.8	6,029	297	60.6	4.9	0.18	80 | 20 | 0	0.40
S-H1	1975	B4	40.3	3,295	55	63.0	1.7	0.11	80 | 0 | 20	0.35
S-H2	1993	A4	40.4	6,057	126	72.9	2.1	0.13	100 | 0 | 0	0.50
S-H3	1990	A4	40.6	5,464	344	57.8	6.3	0.22	90 | 10 | 0	0.40
S-H4	1981	B3	39.7	5,819	142	70.3	2.4	0.16	100 | 0 | 0	0.45
S-J1	1969	D3	34.2	6,398	98	72.8	1.5	0.10	100 | 0 | 0	0.45
S-J2	1978	C4	42.5	8,637	198	79.3	2.3	0.19	80 | 20 | 0	0.40
S-J3	1981	C4	41.1	8,014	315	75.0	3.9	0.24	20 | 80 | 0	0.45
S-J4	1980	C4	41.0	12,876	352	79.2	2.7	0.20	30 | 70 | 0	0.45
S-J5	1968	C4	38.3	5,937	556	64.8	9.4	0.16	80 | 20 | 0	0.40
S-M1	1990	B3	35.5	8,578	305	76.0	3.6	0.25	70 | 0 | 30	0.40
S-M2	1975	C3	34.0	12,183	245	84.0	2.0	0.24	30 | 70 | 0	0.35
S-M3	1981	A3	33.0	9,799	55	71.0	0.6	0.12	90 | 10 | 0	0.45
S-M4	1978	A3	35.6	6,085	249	72.7	4.1	0.20	100 | 0 | 0	0.45
S-M5	1990	A3	31.0	7,776	290	67.3	3.7	0.22	100 | 0 | 0	0.45
S-M6	1979	D3	29.8	11,231	1,150	66.6	10.2	0.24	50 | 0 | 50	0.45
S-S1	2013	C4	39.2	9,197	162	75.3	1.8	0.14	30 | 70 | 0	0.45
S-S2	1980	B4	39.7	6,071	438	64.3	7.2	0.20	100 | 0 | 0	0.50
S-S3	1972	B4	38.4	8,603	398	77.5	4.6	0.20	70 | 30 | 0	0.45
S-S4	1998	C4	33.7	9,663	1,130	81.0	11.7	0.30	80 | 20 | 0	0.40
S-S5	2015	B4	40.9	3,621	5	67.4	0.1	0.14	100 | 0 | 0	0.45
S-S6	2005	B4	38.6	7,789	10	77.3	0.1	0.09	20 | 80 | 0	0.50
S-S7	1983	B4	40.6	7,867	223	76.4	2.8	0.22	60 | 35 | 5	0.35
S-S8	1995	B4	37.4	8,707	945	81.3	10.9	0.23	70 | 20 | 10	0.40
S-S9	1989	C4	35.6	6,485	905	74.8	14.0	0.25	90 | 10 | 0	0.45
S-S10	1920	C4	35.3	6,687	205	74.5	3.1	0.22	50 | 30 | 20	0.50
S-S11	1987	B4	40.2	6,577	145	75.5	2.2	0.24	20 | 80 | 0	0.40
S-S12	2011	B4	40.0	13,937	204	82.9	1.5	0.16	30 | 70 | 0	0.35
S-S13	2000	B4	38.5	5,964	85	72.7	1.4	0.17	80 | 0 | 20	0.45

As one of the main insights of this study, the shaded area that exists in the school playground has been quantified, and the percentage that it represents of the total outdoor area is also calculated. The shade/outdoor-space percentage obtained is very low, both in primary and secondary schools, with percentages generally lower than 10% of the outdoor space, and in certain exceptional cases ranging from 10% to 15% (P-G3, P-M5, S-S8, and S-S9). It should be noted that more than 60% of the selected centres have a shade percentage lower than 5% with respect the total outdoor area, which demonstrates the nullity of shade in schools located in southern Spain, where temperatures often reach over 35ºC during the school term. This percentage of shaded area is far from the recommended 20-30% of shade provided by vegetation to achieve an appropriate balance [27,49], especially when considering the obligations for the provision of other open spaces, such as sports fields.

Following these results, Figure 3 represents the relationship between the year of construction of the schools and the percentage of vegetation area of their outdoor space, so that relationships can be identified between the architectural patterns of each period and wooded areas. Each selected primary and secondary school is represented by a point and it is highlighted that, with certain exceptions, most of the schools built between 1970 and 1990 present a percentage of vegetation of only approximately 3-5%, which shows that, for over 30 years, there has been a lack of trees or other shading architectural strategies in their design patterns. Furthermore, a second marked region indicates that the majority of schools built between 2000 and 2015 also incorporate a percentage of less than 5% of vegetation of their outdoor space, either because they have selected small trees with low compactness to cast shade or that the school's design patterns have not taken into account spaces for gardens, wooded areas, and/or shaded areas, which results in a shortcoming of bioclimatic techniques for warm temperatures. Figure 4 highlights the extremely low percentage of vegetation that exists in the school playgrounds in relation to the percentage of the outdoor space on their entire plots, and reveals that the bulk of the sample has under 10% of their outdoor spaces covered by vegetation, and that outdoor spaces mostly represent approximately 70 to 85% of the total area of each plot.

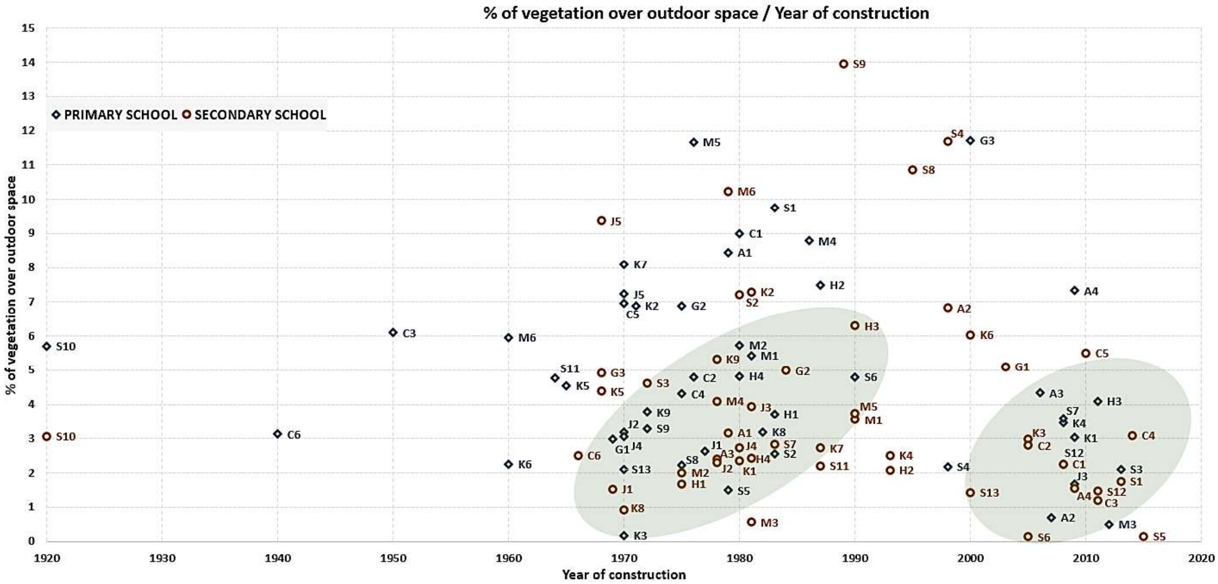

Figure 3. Relationship between the year of construction (X) and the percentage of vegetation (Y).

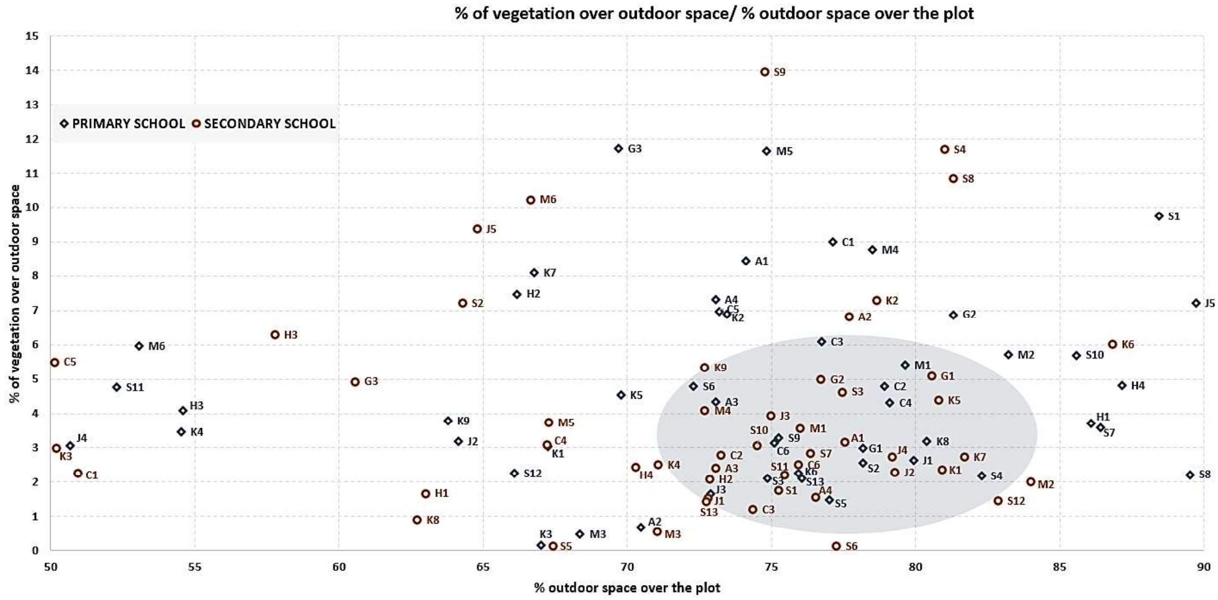

Figure 4. Percentage of vegetation coverage (Y) and percentage of outdoor space of the entire plot (X).

Regarding the proportion of ground materials in schools, Figure 5 analyses, for primary and secondary schools, the proportion of hard, earthen, and green materials in each centre, and also incorporates the SRI value, which ranges between 0 to 1, represented as a red dot for each column. The graph shows that the vast majority of schools present a major predominance of hard paving, mainly composed of stone materials, with an average percentage of 78% for primary schools and 70% for secondary schools, and even reaches 100% in several schools. In fact, this pattern has evolved in recent years towards the greater implementation of hard paving in schools, which has a negative impact on the overheating of the ground in hot seasons and an absence of bioclimatic techniques to guarantee the comfort and well-being of students. This trend of covering the outdoor space of schools with hard, predominantly dark grey materials implies that the mean SRI values are generally around 0.40, and even reach 0.20 (P-J1) in certain cases, with a very dark ground in a hot area, which causes massive absorption of solar energy and irradiation during the hottest hours, thereby increasing the temperature of the ground and generating a more intense heat-island effect.

The surface of arid or earthen materials is generally limited to a minor proportion, of approximately 20% of the total. However, in certain schools, it represents the largest portion of their ground (P-C4, P-J5, P-S6, S-J3, S-S6), and this pattern is reflected in SRI values above 50%, which translates into a greater rejection of solar energy and a more pleasant temperature. With regard to the green ground areas, a remarkably low number of centres have gardens or lawns (S-M6, S-M1), generally due to the water consumption and maintenance work required, although it is highly beneficial in terms of reducing the temperature of the ground. These results demonstrate the great utility that a classification of the ground in schools represents, in an effort to increase the percentage towards earthen or green surfaces with lighter colours, and towards raising the average SRI value closer to 60%, which, together with a larger shaded surface, would lead to greater thermal comfort in these spaces in the summer months.

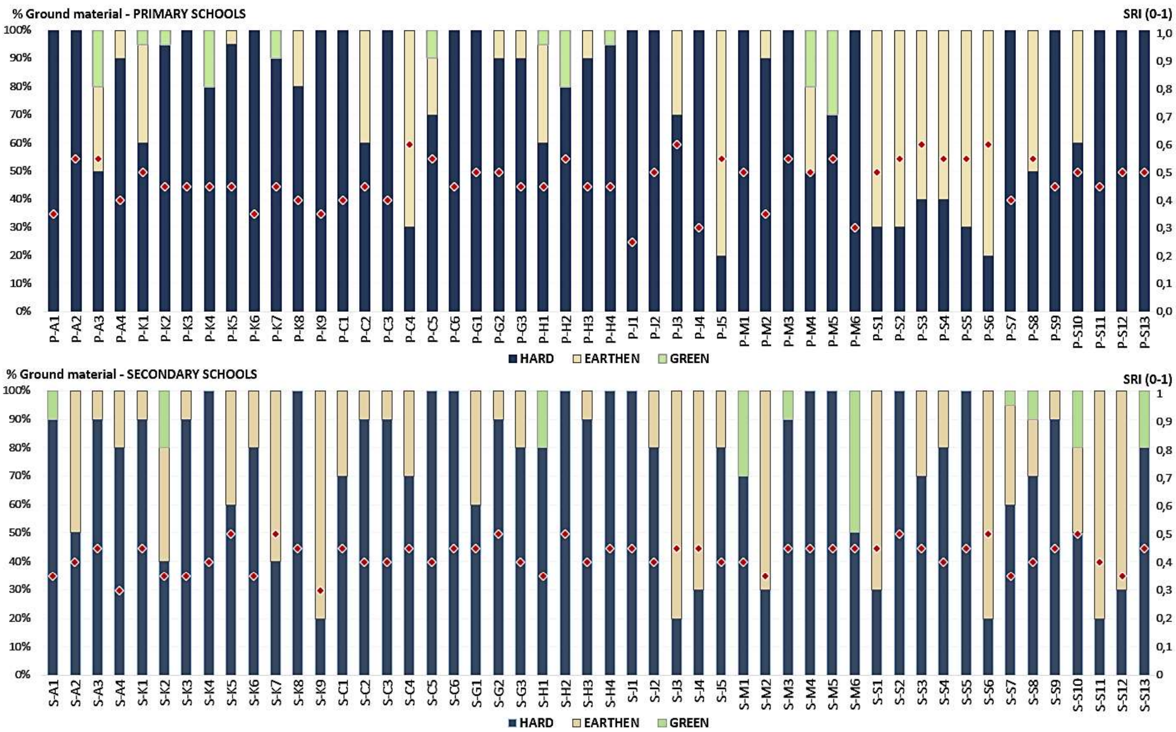

Figure 5. Proportion of ground materials and SRI mean values in the outdoor space of each school.

The technical visits and measurements carried out in the selected schools and the work with remote sensing tools have enabled the schools to be represented in graphic diagrams for the exhaustive characterisation of the selected sample. This characterisation follows the factors determined in the methodology and aims to identify areas where vegetation is concentrated, to ascertain the impact of heat on the paving, and to study the proportion of exterior space with respect to the building.

For the primary and secondary schools in the sample, Figures 6 and 7 respectively represent the NDVI index per surface obtained in June by the remote sensing tool. The map of each selected school also indicates, by means of a colour scale, the presence of trees in the outdoor spaces of the schools. The results show a global view of the scarce presence of vegetation, mostly with dark red colours that represent the inexistence of wooded areas, thereby enabling a visualisation of the distribution of trees and the characterisation of the ground in a single graphic diagram. There are certain minimum areas in yellow that indicate the presence of vegetation, normally disaggregated in the plots, although it is the green colour, closer to NDVI values of 1, (which are the least common areas), that indicates the presence of heavier foliage and perennial trees that cast shade.

Lastly, Figures 8 and 9 represent the proportion of outdoor space of primary and secondary schools with respect to the building area on the plot. A colour scale, adjusted to the mean SRI value obtained for the ground and ranging between 0.20 and 0.60, shows the presence of very dark colours that indicate materials that are highly absorbent of solar energy in certain schools with a very large surface area of outdoor space. It also reveals the various scenarios in the relationship of outdoor space with respect to the total area of the plot.

These maps offer a global and particular visualisation of the characterisation of the schools with respect to their wooded and paved areas, as a complement to the main tables and previously analysed graphs. It is shown that there are a very low number of trees, that the predominant paving has low SRI values, and that even secondary schools generally have a higher ratio of exterior surface to the building area than do primary schools. These results introduce key findings that imply a greater need for the implementation of action strategies that integrate vernacular techniques for coping with hot climates and funding provision for their watering supply and maintenance, which would reduce the global warming impact and increase the well-being of users in educational buildings. Another major insight focuses on the use of remote sensing tools as a mechanism contributing towards reaching a better understanding of the design and performance of outdoor spaces in schools, and towards their incorporation into the architectural-technical disciplines that have hitherto failed to enhance said resource. These remote sensing tools offer a great opportunity for their application in future environmental research into the built environment [37].

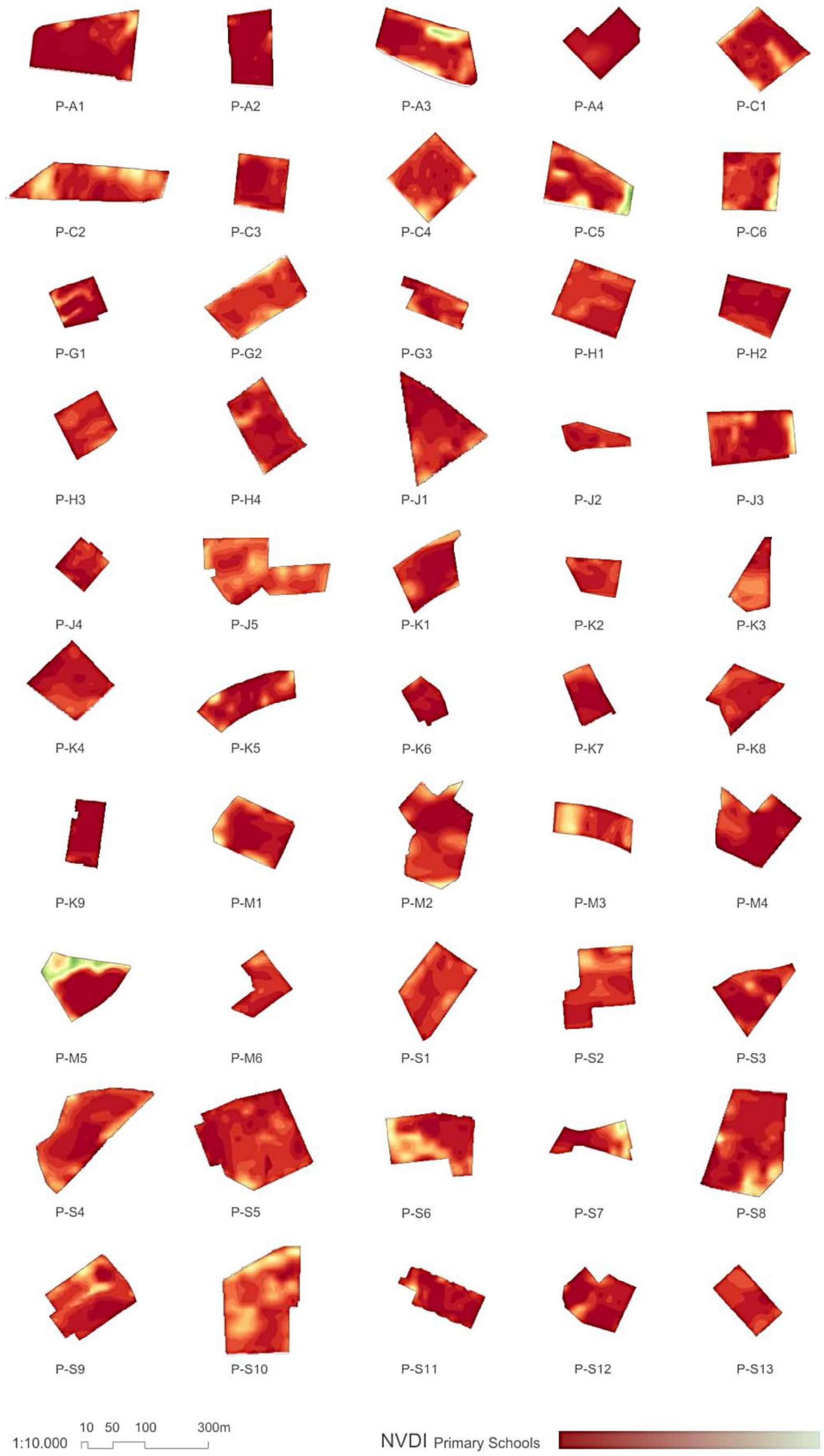

Figure 6. Graphic representation of NDVI values on the plot area in primary schools.

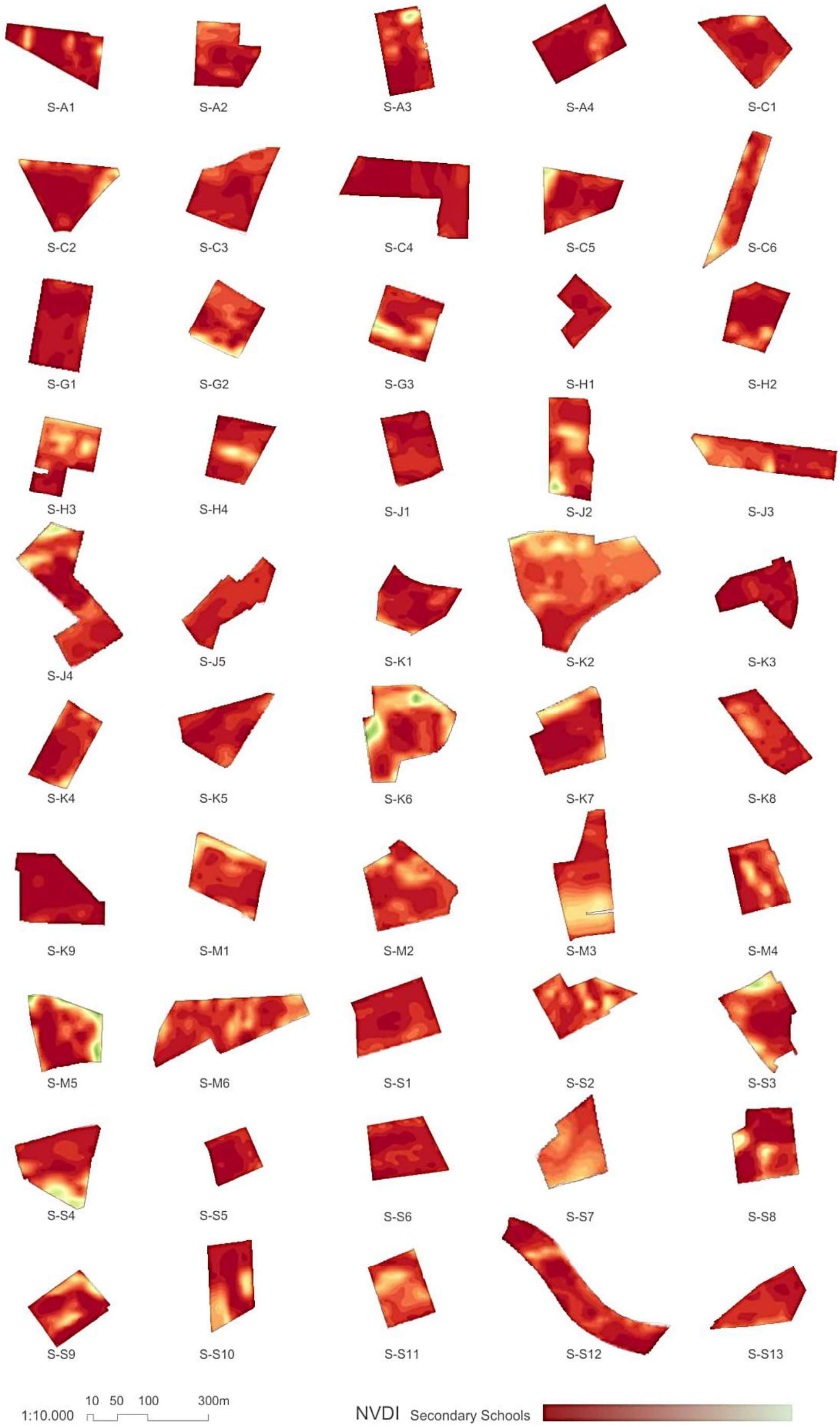

Figure 7. Graphic representation of NDVI values on the plot area in secondary schools.

Figure 8. Outdoor area with respect to Primary School buildings and mean SRI value on a scale.

Figure 9. Outdoor area with respect to Secondary school buildings and mean SRI value on a scale.

5. Conclusions

This paper characterises, quantifies, and assesses the outdoor environmental quality of a representative sample of 100 selected schools in the southernmost region of Spain, in an effort to diagnose and verify the outdoor thermal performance and design adaptation to the imminent global warming in the open spaces of existing schools located in a hot climate. The research is motivated by the need to identify the inappropriate design patterns in recent years of outdoor spaces of schools, by means of technical measurement and remote sensing tools, which determine action mitigation strategies to reduce heat-island effects, through the use of bioclimatic techniques that would guarantee the thermal comfort of students during the increasingly hot summer months.

The ~~uniqueness~~novelty of this research is that it focuses on discussing certain parameters that influence the outdoor environmental performance of schools, while considering the increasing inconveniences that emerge each year when high temperatures hit during the academic year. In addition to the design patterns in which the schools were built in the corresponding period, one of the main findings of this study is that there has recently been a trend of laying concrete paving and simultaneously reducing the number of trees that cast shade in order to reduce the basic tasks of maintenance required thereof although this also alarmingly reduces the comfort and usability of these spaces for students.

Unlike other studies, this research delves into the planimetric analysis of the open space of each selected school, and combines the quantification of the shaded space, using the NDVI index, together with a ground classification and an assessment of its mean SRI values. All this ~~work~~original approach has been carried out on a representative sample of 50 primary and 50 secondary schools, which correspond to 50 municipalities, where average maximum temperatures of over 35 ºC are reached in the hottest months of the school year.

The conclusions drawn from these results show that the percentage of shade in the outdoor spaces of schools is extremely low, whereby more than 90% of the schools in the sample have less than 10% of their outdoor space in the shade, with the average value below 5%, and mean NDVI values ranging between 0 and 0.3, in schools located in very hot climatic zones. Furthermore, approximately 70% of the centres have more than 80% of their area paved with hard materials, concrete, and/or stone tiles, whose SRI values are generally low. In fact, only 10% of the schools studied present all three types of ground materials studied (hard, earthen, and green areas), although hard paving still represents the majority of these materials. These results demonstrate the uncomfortable conditions of these school playgrounds, in that their percentages of vegetation remain far from sustainable levels (between 20 and 30% of the outdoor space), as do their values of intermediate SRIs, which fail to block the absorption of solar radiation, which is advisable in ranges between 0.6 and 0.7.

The study attains the objectives of the research by offering quantified results through standardised variables, thereby demonstrating the serious discomfort of students in school playgrounds in the warm months at 11:00 a.m. It also contributes towards the exhaustive detection of excessive concrete paving in schools along with the scarcity of existing trees that cast shade, and addresses the trend of paving outdoor spaces of schools, by incorporating new arid and vernacular materials that prevent the absorption of solar radiation and reduce the consequences of the heat-island effect. Although the application of this study is focused on schools from Andalusia, this research also introduces relevant implications for other schools located in warm climates, since it identifies and provides the parameters and guidelines to be followed, and hence this characterisation methodology can be replicated in schools in countries whose outdoor spaces in schools are affected by high temperatures.

The implications of the study indicate: establishing new action strategies in urban policies and regulations that promote bioclimatic actions in schools towards the recovery of vernacular architecture in school playgrounds in southern Spain; increasing vegetation and wooded areas; reducing the percentage of hard paving; and incorporating fountains with water or ponds for rainwater collection. The results obtained establish a broad and exhaustive diagnosis that allows these open areas to be transformed into pleasant and usable spaces for teachers and students, with shade and a combination of hard, earthen, and green surfaces.

This research raises awareness of the need to generate new management models for outdoor spaces in schools that facilitate their adaptation to future environmental changes by means of bioclimatic strategies, which ~~introduce~~contribute with basic notions regarding the importance of shade, vegetation, and the maintenance of trees, which can promote actions from the educational community. In fact, subsequent future studies along these lines will be aimed at evaluating the impact of the implementation of citrus tree species, very common in the Mediterranean climate, such as orange and lemon trees, as a strategy for heat-island mitigation, the reduction of CO_2 levels, and for the generation of shade in schools. Finally, further development of this research is intended to be focused on incorporating social studies, carried out on students surveyed regarding their outdoor comfort while using the school playground during the morning, thereby obtaining future models of decision-making in renovation strategies according to the technical diagnosis, remote sensing, and social demands from users.

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