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Sustainable Green Roof Ecosystems: 100 Years of Functioning on Fortifications—A Case Study

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Received: 2 April 2020; Accepted: 5 June 2020; Published: 9 June 2020

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Abstract: Green roofs have received much attention in recent years due to their ability to retain rainwater, increase urban diversity, and mitigate climate change in cities. This interdisciplinary study was carried out on three historical green roofs covering bunkers in Wrocław, located in southwestern Poland. It presents the results of a three-year investigation of the water storage of these roofs. The study also presents soil conditions and spontaneous vegetation after their functioning for over 100 years. The soils covering the bunkers are made of sandy, sandy-loam, and loamy-sand deposits. This historical construction ensures good drainage and runoff of rainwater, and is able to absorb torrential rainfall ranging from 100 to 150 mm. It provides suitable conditions for vegetation growth, and forest communities with layers formed there. In their synanthropic flora, species of European deciduous forests dominate, which are characteristic of fresh or moist and eutrophic soils with a neutral reaction. Some invasive species, such as *Robinia pseudoacacia*, *Padus serotina*, and *Impatiens parviflora*, also occur with high abundance. Nowadays, historical green roofs on fortifications, although they have lost their primary military role, are of historical and natural value. These roofs can promote the nonmilitary functions of historical fortifications in order to strengthen the ties between nature and heritage. Protecting and monitoring historical green roofs should be included in the elements of the process of sustainable development and the conservation of these structures in order to mitigate climate change in the outskirts of the city. For this, it is necessary to ensure proper conservational protection, which, in addition to maintaining the original structure, profiles, and layout of the building, should include protection of their natural value.

Keywords: green infrastructure; technogenic soil; soil water retention; synanthropic flora; urban vegetation; heritage protection; fortified landscape

1. Introduction

The development of urban areas often negatively affects the natural environment in terms of soil erosion or the reduction of available water resources for plants [1]. These changes may also occur in historical areas [2], an example of which may be historical fortifications (hereinafter referred to as HF). Protecting their cultural, historical, and natural values is a new challenge in the face of climate change [3], since HF no longer exist in the environmental conditions for which they were designed. This applies, inter alia, to earthen fortifications with soil used in their construction (e.g., embankments, traverses, etc.), which are an integral element of HF. An example of such earthen coverings are green roofs, most often made up of sandy deposits that tend to lose water that is collected within due to low retention. The more frequent occurrence of prolonged dry periods may cause the health of plants to deteriorate and may even lead to the loss of certain sensitive species grown on such green roofs. Therefore, learning about their construction and how they function is important for maintaining integrity within historical urban landscapes [4]. Likewise, despite supporting sustainable urban development [5], these heritage sites can be used as "living laboratories to implement mitigation strategies and highlight better mitigation and adaptation practices" [3]. Furthermore, according to Fluck and Wiggins [6], the preservation of heritage and the historical character of a landscape has a positive effect on communities, while the ways in which heritage is managed can lead to a better understanding of the effects of climate change in other areas.

Currently, many historical fortifications, together with their vegetation, constitute "green islands" among the new housing estates of many cities. They may be threatened by urban sprawl, not only in their immediate vicinity, but also within the borders of the plots of land belonging to former fortress. In addition to the growing interest among developers looking to build residential buildings on the grounds of historical fortifications, there is also a growing group of city dwellers seeking opportunities to actively protect monuments, often with their own hands. Practice shows, however, that providing deteriorating monuments with proper care and use (i.e., adapting them to new functions) can be a challenge for new hosts looking for a proper way to maintain genius loci.

On the other hand, professional practice reveals that in Poland, in the process of renovating and adapting the fortifications built at the turn of the 19th and 20th century, investors saw an alternative to historic green roofs in the form of creepers or new roofing made of sheet metal. This came to light as a result of work conducted, including the partial or complete replacement of damp coursing or the existing ventilation system. With full replacement or the introduction of insulation, preservation of the original green roofs is not practiced. The result is a new, turf roof, also using roll-out grass.

From a conservational perspective, the valuable elements of historical green roofs are their original material and profile (layout) of the buildings covered in this way, including their integration with the surrounding landscape. Their historical value stems from the preservation of as many original elements of the fortifications as possible. Currently, according to the conservational recommendations (the procedure of conservational conventions) in Poland, when a building requires a thorough replacement of damp coursing, the emphasis is on restoring green roofs using couch grass (*Elymus repens*), for instance. However, every such case is individually considered due to various forms of conservation protection, fortress schools, types of buildings and their construction, the building materials used, and the historical layers found in such fortifications.

Environmental aspects related to climate change often fade to the background, opening the way to dangers in the form of "idealized scenery," resulting from the premise of restoring historic monuments to their former military glory of yesteryear. After some time, counterproductive practices come to light involving the degradation of historical sites, often resulting from a desire to tidy them up. Degradation may affect the whole area or part of it (e.g., earthworks and green roofs on buildings) regardless of the form of their conservational protection. This can last for years or can take the form of one-off incidents. As a result, there are changes in the form of soil erosion, water retention, and disturbance in plant coverage (Figure 1).

Figure 1. Examples of work that cause soil and plant ecosystem degradation of historical green roofs: (**a**,**c**) Infantry shelter before and after restoration; (**b**,**d**) infantry shelter before and during restoration works with a new green roof, Wrocław, Poland. 2012 and 2016, sourced from the author Łukasz Pardela's archive.

Harmful practices resulting from increased anthropopressure include the elimination of earthen forms permanently connected with fortifications (e.g., earth coverings often considered to be unnecessary), replacing historical soil cover with present-day extensive green roofs, the hardening of road surfaces, soil exchange (e.g., foundations for new roads), the cutting of all vegetation causing excessive insolation of structures (exposure of earthen forms), and improper maintenance involving the raking and removal of fallen leaves instead of composting or leaving them in place as litter. Such actions are not conducive to mitigating the effects of burgeoning climate change. Despite the preservation of heritage values such as authenticity and integrity, they often pose a greater threat than just leaving the building or other military structure alone while systematically monitoring its condition.

This research studies green roofs built on historical infantry shelters, commonly referred to as "bunkers." Their role and significance for urban areas in terms of habitat conditions and retention potential are worth learning more about. HF are an example of historic buildings that were designed in conjunction with the surrounding landscape. This meant taking into account unfavorable humidity conditions in the form of both excess precipitation and water shortages, which is why these areas have demonstrated resistance to fluctuations in soil humidity. The fortification buildings would not have stood out too much in the surroundings, and so were "greener" than the surrounding landscape, e.g., during a drought. This also applied to the vegetation cover, whose species composition was similar to that occurring in adjacent areas. Green roofs on fortifications were often elements of the fortifications elevated above the surrounding area, making them visible from the ground and from the air. In addition, the long period that elapsed since the construction of the fortifications and, above all, the loss of their original functions and the related lack of maintenance, causes the accumulation of organic matter (litter) on an unprecedented scale, e.g., in urban parks. Similarly, abandoning the cultivation of greenery, along with progressive succession, has caused an increase in woody vegetation, which partly limits the direct influence of sunlight on the vegetation of green roofs. Green roofs on fortifications are also an example of the use of natural substrates, on which vegetation has been developed throughout the decades via natural succession (including what is not currently recommended, e.g., in Belgium and the Netherlands for roofs (e.g., *Acer platanoides*), which is difficult to observe in the case of green roofs on urban buildings.

On the other hand, the research results can help to highlight values that for years have lain beyond the main trends of research on the functioning of green roofs and technogenic soils in the city, as well as the transition from a rural to a suburban landscape. The inspiration to undertake this topic was the ambition and impulse to promote the nonmilitary functions of HF in urban areas in order to strengthen the ties between nature and heritage. Nowadays, HF, as well as historical parks and gardens, can influence climate change in a condensed form over a limited area [2]. In the case of this research, green roofs have sheltered HF for over a century. Since their construction, these roofs have blended into the agrarian landscape [7,8]. After time, some of the green-roofed shelters lay on the city peripheries, and today they mimic natural ecosystems in these areas. Therefore, even understanding the short-term performance of these historical green roofs in different seasons of the year and weather conditions is of great importance within the process of adapting diverse areas in cities to climate change. This is also connected with developing biodiversity strategies for cities, especially highly polluted ones such as Wrocław, located in southwestern Poland [9].

Consequently, there is an important role for cultural heritage sites to play in terms of adapting to future climatic impacts [6]. This interdisciplinary research into heritage, interrelated with historical and natural environments, supports sustainable development, the management of cultural heritage, and the mitigation of climate change in cities.

Therefore, through interdisciplinary research, this paper presents the following:

- The characteristics of technogenic soils formed on the roofs of historical fortifications based on field studies;
- The present vegetation growing on shelter green roofs with some of the species' ecological characteristics;
- Defined directions for the development, restoration, and protection of historic green roofs in the city peripheral areas in the context of the challenges posed by a changing climate.

1.1. Historical Green Roofs

Green roofs sheltering historical fortifications, as a result of a long military engineering tradition, have been used in fortifications for centuries [10]. They are similar to present-day "earthen sheltered" buildings with green roofs, which are beneficial to wildlife and the environment [11]. In terms of fortifications, green roofs are "living roofs" on top of bunkers and can be defined broadly as engineered constructions that include environments suitable for well-adapted plant species [12]. Therefore, their construction is similar to intensive green roofs [12,13]. As artificial habitats, like any constructed ecosystem, they evolve over time [13].

The transformation of green roofs has been the subject of numerous studies over the years [14–17]. A good proportion of the research concerned the historical origins and evolution of intensive green roofs in many countries [18–20]. Simultaneously, many authors indicate the need to focus on researching "real-life" examples of green roofs in order to determine the benefits arising from deeper substrates in different weather conditions [21] and vegetation dynamics on green roof performance and design [13], as well as biodiversity conservation [22–24].

Nonetheless, the most commonly examined facilities are green roofs related to civil architecture, including historical [18–27]. This also includes engineering facilities—for example, the water filtration plant near Zurich (Wollishofen) in Switzerland built in 1914 [28,29]. Research related to green roofs on HF, by contrast, is rather rare. However, the technogenic soils constructed on 19th century heritage fortifications have been the subject of some research. In a study by Jankowski et al. (2013), three soil formations located on three different fortified heritage sites (fort, infantry shelter, and ammunition storage) were selected for detailed soil formation analysis [30], while a study was carried out by Pardela and Kowalczyk (2018) to estimate the variation of soil water retention in six soil formations of a single infantry shelter heritage site [31].

1.2. How Green Roofs Function in an Urban Environment

The ecosystem services (ESS) and disservices (EDS) of green roofs have been widely discussed in numerous works [14,32,33]. ESSs include the improvement of storm water quality and quantity, a reduction in the rate and volume of runoff [21], mitigation of the urban island heat effect [17], facilitation of energy efficiency by reducing maintenance costs, fire retardation, or enhanced noise reduction [34]. Green roofs may also improve air quality and carbon sequestration [35], support wildlife and habitat biodiversity, enhance rooftop agriculture and roof life, increase educational opportunities, and boost health [19]. EDSs include, for example, stormwater quality and quantity with the leaching of nitrates (nitrogen sink) and soluble carbon, which decreases the runoff water quality [36]. For some buildings, thermal mass increased by thick substrate layers on the building and the downward movement of heat leads to higher cooling costs [37]. If green roofs are located too high above the ground, they can offer ecological traps for many species [38] or attract nuisance wildlife [39].

In addition to the ongoing "present-day" functionality of green roofs, the lost historical functions related to the green roofs on HF are worth mentioning and include: hiding flat roofs against aerial observation, draining rain water from the building structure, protecting flat roofs (e.g., the top layer features tar waterproofing), retarding fire (which may be caused by enemy shelling), and limiting the damage inflicted by artillery grenades or shrapnel.

1.3. Green Roofs on Shelters in Historical Guidelines

Unfortunately, little is known about the details of soil layers of many of the green roofs on historical shelters. From general guidelines for laying earthen covers in the German Empire shortly before 1900, it is known that the thickness of green roofs historically ranged from 30 to 50 cm [40,41]. After 1900, the earthen covering of concrete shelters consisted of a 20–30 cm layer. This provided the roof insulation with sufficient protection against insolation and shielded flat roofs from air reconnaissance (from balloons and, later, planes). A guideline from 1905 indicated that on a (green roof) covering, it was possible to sow grass species on a bed of clay mixed with sand [42]. This provision also indicated that flat roofs should be maintained with herbaceous vegetation without introducing any shrubs. Similarly, the trampling and destruction of forest litter on earthworks was forbidden.

2. Materials and Methods

2.1. Study Sites

The study was conducted in the Wroclaw city area (Figure 2). The rainfall in Wrocław is highly variable: the annual total rainfall ranges between 318 and 892 mm, while the average annual precipitation in the 20th century was 583 mm. The average annual temperature is 9 °C, and the annual temperature amplitude is 19.2 °C. Winters are short (65 days) and mild, with frequent periods of warming in February of up to 10–15 °C.

Three historical infantry shelters (more accurately referred to as 'Infanterie Raum') (Table 1, Figures 3 and 4), whose construction is described in literature regarding fortifications, were selected for the research [43,44].

The studied shelters (referred to as S-1, S-2, and S-3) are a representative group of military fortifications with well-preserved green roofs. Shelters S-1 and S-2 are the central points of the infantry works (Infanterie Stützpunkt), which consisted of smaller shelters and a permanent shooting position. Shelter S-3 is a single facility partially surrounded by an embankment. Their origins date back to the quarter-century preceding the First World War, when a ring of shelters was built around the city as part of the fortification of the former German city of Breslau (now Wrocław). After the Second World War, Wrocław found itself in Polish territory [8]. The historical surroundings of the researched facilities are presented in Figure 4. The largest changes in the landscape and land cover in the surroundings of the studied facilities took place after 1947. As a result, some of the areas around the fortifications were allocated as allotment gardens for workers (now family allotment gardens) from divided agricultural land, and after the political transformations of 1989, new housing developments appeared, along with expanded road and flood protection infrastructure.

Around the described shelters, we can now find various soil units, including Fluvisols, Luvisols, Czernozems, and Podzols [45]. Adjacent vegetation consists mainly of garden flora, abandoned fields, roadsides, levees and retention ponds, and other ponds of ruderal areas. Further away, some fragments of oak-hornbeam and alluvial forests are preserved. In the vicinity of S-1, there is a landfill with the remains of bonfires.

Shelters S-1 and S-2 with roofs are currently located on the outskirts of the city of Wrocław on low hills bordering the floodplain of the Widawa River, protected against flood waters thanks to embankments serving as shooting positions. These shelters rise above the surrounding area. A pair of ponds are located at the S-2 facility, where rainwater from the entire facility was drained. In turn, shelter S-3, with a green roof is recessed in the ground below the surrounding area and is located near railway lines, whose access it was supposed to defend. In the 1960s, allotment gardens were created nearby, and still exist there today. All the researched facilities were abandoned by the army and civil defense in the early 1990s. Facilities S-1 and S-3 are somewhat secluded, while S-2 is fenced and guarded by a local association. An illegal landfill was created in the immediate vicinity of S-3, which is regularly cleared out. In recent years, there has also been growing anthropopressure in the form of the organization of illegal obstacle courses (S-1) and the organization of nighttime events (S-3). The flat roofs of these shelters constituting the structure that holds the substrate of green roofs were made in two ways. The earlier type of the flat roof was 3 m thick in a three-layer (brick-sand-concrete) structure (which is the case for S-1 and S-2). In this case, the outer part of the roof was concrete with granite aggregate with waterproofing made from hydraulic cement. The later type of flat roof featured a monolithic concrete flat roof that was 2.20 m thick, with tar waterproofing (S-3). Both types of roofs sloped slightly towards the outside of the building. Currently, the shelters under study are under conservation protection and are the property of the municipality of Wrocław or the Treasury. The buildings are open to the public. One (S-2) is currently under conservation and restoration works to serve the local community.

Table 1. Summary of the characteristics of each green roof covering the shelters.

Study Site	Location	Historical Name	Year Installed	Approx. Size (m^2)	Age (when Surveyed)
Shelter S-1	51°9′1.934″ N 17°5′13.829″ E	Infanterie Stützpunkt 4	1891	488	128
Shelter S-2	51°9′53.118″ N 17°2′37.137″ E	Infanterie Stützpunkt 6	1891	488	128
Shelter S-3	51°4′26.654″ N 17°4′23.994″ E	Infanterie Raum 20	1900	420	119

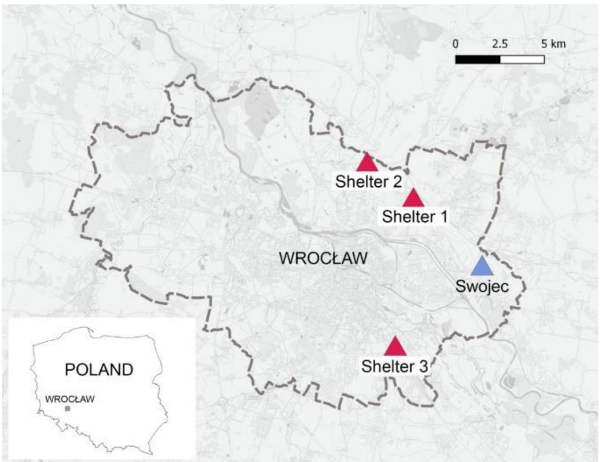

Figure 2. Location of the shelters and the Swojec station within the borders of City of Wrocław, Poland.

Figure 3. The green roof shelters in winter, 2016, and spring, 2019. From left: Shelter S-1 (**1a**–**c**), S-2 (**2a**–**c**), and S-3 (**3a**–**c**). Sourced from the author Łukasz Pardela's archive.

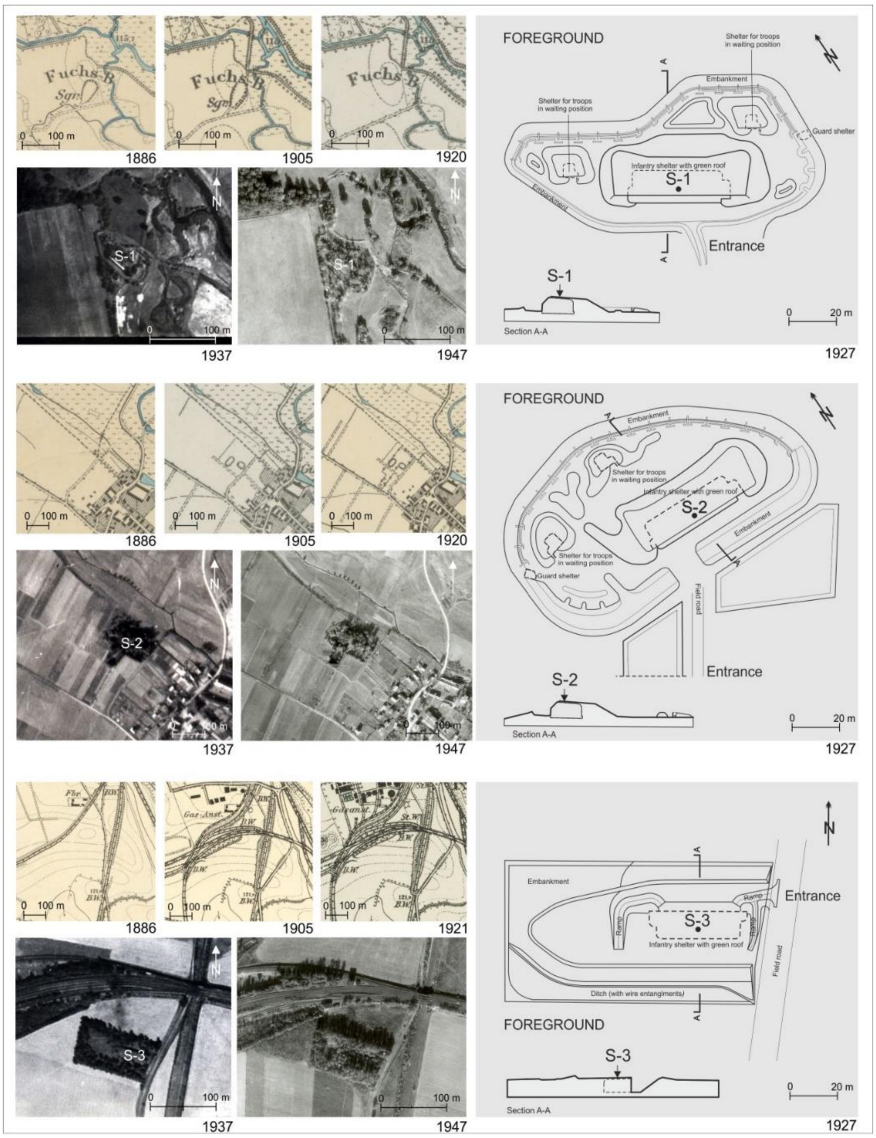

Figure 4. Historical landform and land use around the studied facilities in the years 1886–1947 [8]. The fragments of the topographic maps Meßtischblätter 2828 (4868) and 2892 (4968) come from the collection of Staatsbibliothek zu Berlin—Preussischer Kulturbesitz ©. Aerial photographs (1937 and 1947) were taken from the authors' archives and the state archives in Wrocław © (reference number 328/II; 244, 239, 281). Drawings were made based on documentation of the League of Nations Archives in Geneva (1927) and field measurements.

2.2. Analytical Methods

2.2.1. Historical Records

In order to identify the historical appearance, construction and maintenance of the study sites, documents and references from historical archives and libraries in Poland, Germany, and Switzerland were collected. In particular, technical instructions and documents from the 19th to the 20th centuries were selected and interpreted. Historical topographic maps from 1860 to 1938, as well as aerial and satellite photos from 1926 to 2018 were also analyzed for any changes in landform and land cover, both within the plots of the former fortress and in their immediate vicinity. Due to the military significance of the facilities, they were usually not marked on topographic maps (Figure 4), nor have historical drawings or logbooks detailing the construction and cultivation of the fortifications survived.

2.2.2. Soil Studies

Within the scope of the fieldwork conducted, the profile of the soil on the surface of the shelters was described. The morphological features were characterized, with particular emphasis on the: color, structure, and presence of redoximorphic features and artefacts. Samples were taken from the soil levels for laboratory analysis. In order to determine the retention capacity, samples were taken in Kopecki metal rings with a volume of 100 cm^3. The retention properties of the soil samples were analyzed in the pF value (soil moisture tension, pF = log(h) cm H_2O) 0–2 and pF 2–2.7 range using Eijkelkamp sand and kaolin-sand [46]. Soil retention properties in the 3.2–4.2 pF range were measured in Richard's high-pressure chambers [47].

The textures of the soils were determined using an aerometric sieve method in accordance with the PN-R-04032 standard [48]. The names of the soil granulometric groups were determined on the basis of the Polish Soil Science Society's classifications [49]. The soil reactions were potentiometrically measured in H_2O (water-soil ratio of 1:2.5) [50]. The soil types and subtypes were determined using the Polish soil classification [51]. International soil units were determined using the classification of the World Reference Base for Soil Resources (FAO-WRB) [45].

2.2.3. Soil Water Storage

Analysis of soil moisture distribution on the shelters was performed on the basis of measurements of three field profiles located in central points of the green roofs. Soil sampling and measurements were made with an Eijkelkamp auger. In the areas where moisture was to be checked, investigative borings were drilled down to the flat roof. Soil moisture was measured using the direct method, with a handheld meter for measuring soil volumetric moisture, based on the time domain reflectometry (TDR) FOM/mts reflectometric technique with an FP/mts probe. The probe was placed in holes made with a hand drill as required. Systematic moisture measurements were taken once a month on average from April to October in 2017–2019. The meteorological conditions during the period of moisture measuring were based on data from the Swojec station (51°4′25.9″ N, 17°4′22.8″ E, Bartnicza Street) (Figure 2, Tables 2 and 3) located, like the facilities under the research objects, on the outskirts of the city. At the same time, visual observation was carried out and the necessary photographic documentation was completed.

Table 2. Periodic and annual atmospheric precipitation, P (mm) in the hydrological years of 2017–2019 in the context of a longer period according to the Wrocław-Swojec station.

Years	P (mm)			
	XI-X	XI-IV	V-X	IV-IX
2017	668	219	449	442
2018	415	134	281	260
2019	535	196	339	347
2001–2010	587	216	371	366

Table 3. Average periodic and annual air temperature T (°C) in the hydrological years of 2017–2019 in the context of a longer period according to the Wrocław-Swojec station.

Years	T (°C)			
	XI-X	XI-IV	V-X	IV-IX
2017	9.7	3.0	16.3	15.8
2018	10.8	4.0	17.6	18.1
2019	10.5	4.4	16.7	16.5
2001–2010	9.5	3.3	15.8	15.9

2.2.4. Floristic Studies

Floristic observations were carried out in August during 2019. The occurrence of vascular plant species and their abundance were investigated throughout the entire roof area of each shelter (S-1-S-3). The names of the species were provided by Mirek et al. [52] and their abundances were expressed using a four-point scale. Habitat conditions (i.e., light, soil moisture, trophy, and soil acidity) were rated for the recorded species according to Zarzycki et al. [53].

3. Results

3.1. Soil Studies

The shelter soils consist of sandy, sandy-loam, and loamy-sand deposits spread over a concrete base. The level of the concrete was sometimes covered with wood tar. The thickness of the topsoil (humus horizon) ranged from 14 to 18 cm was mainly caused by diverse microrelief, uneven accumulation of organic matter, and anthropogenic influences (Figure 5). The results of the soil texture analysis indicate an increase in the content of clay and silt particles in soils on the green roofs of S-2 and S-3 shelters in relations to the soil on the green roof of S-1. The soil texture composition offers good drainage and easy runoff for rainwater. Sometimes deeper, more compact soil horizons manifested hydromorphic features. The topsoil is characterized by the presence of anthropogenic admixtures in the form of slag, bricks, mortar fragments, ceramics, and glass, as well as metal debris and nails. The addition of artefacts to the soil was observed from the time of constructing green roofs on the bunkers to the present day. The plant litter is classified as moder-mull type of forest humus and mainly consists of the remains of maple, black locust, and oak leaves. The slightly acidic reaction of the litter often indicates the presence of admixtures made up of building debris. The described soils fall within the broad category of Anthropogenic soils, of the Technogenic soil type and the Konstruktosol subtype with a solid technogenic layer [51]. The soils were examined and classified as Isolatic Dystric Arenic Technosols and Isolatic Eutric Arenic Calcic Technosols [45].

In the studied mineral soil levels, the pH ranged from 4.5 (S-1) to 7.2 (S-3), which indicates a strongly acidic to neutral pH. The pH of the plant litter ranged from 5.0 to 6.6, meaning strongly or slightly acidic.

In the case of the green roofs covering shelters S-1 and S-2, crushed brick and granite aggregate constituted the basic building material used for erecting the shelters. The soil levels in the shelters also contain glass, the remains of malacofauna and *Robinia pseudoacacia* seeds. In turn, the flat roof on top of shelter S-3 is made entirely of concrete and its waterproofing layer is made of wood tar. The green roof over this shelter features an admixture of fine granite fragments, originating from the aggregate used for concrete, and also charcoal.

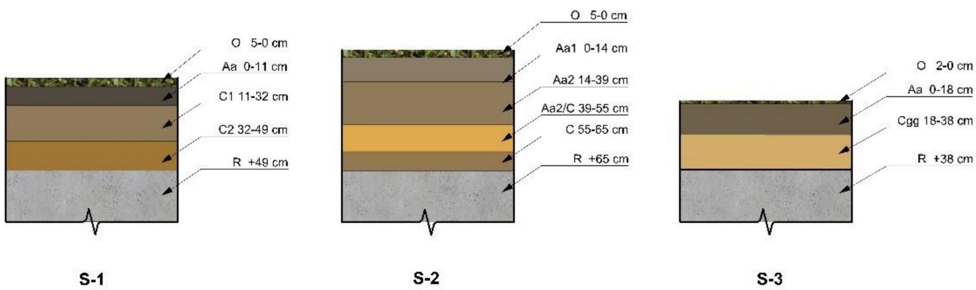

Figure 5. The depth of the soil horizons on the green roofs: O, organic horizon; A, humus horizon; C, parent rock horizon; AC, mix of the horizons; R, lithic rock (ecranic); a, anthropogenic material; g, gleyic properties. The colors of the horizons are shown (gray, brown, yellow, etc.) (description of horizon symbols [51]); S-1, S-2, and S-3 are symbols of the shelters.

3.2. Soil Water Storage

The soil granulometric composition was determined to be diverse. This feature clearly affects the retention capacity of the soil levels and the availability of water for plants. The profile on shelter S-1 represents sandy soil, which translates into the least water retention capacity. However, the water resources available for vegetation on this edifice did not differ greatly and, furthermore, did not fall below the drought period capacity (DPC) over the long term, just like the other green roofs. On shelters S-2 and S-3, the green roof soils were made up of clay in sands, with the S-3 profile containing the most silt. As a result, these roofs have a proportionally greater retention capacity. However, the profile on shelter S-2 revealed the deepest depletion of soil moisture resources of all the edifices studied. Below is a summary of the soil moisture reserves in the context of meteorological conditions between 2017 and 2019 (Figure 6).

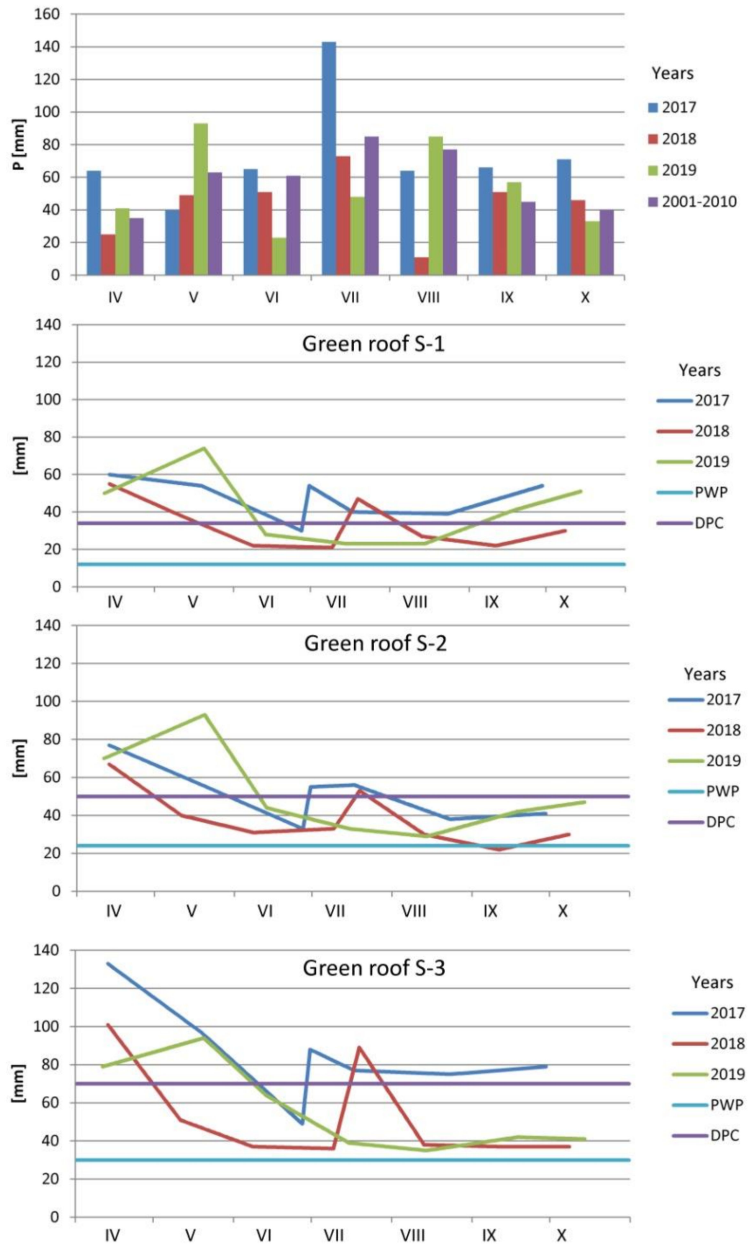

Figure 6. Changes in moisture in the soils on green roofs in the context of the storage capacity of these soils.

In 2017, the rainfall was 14% (+76 mm) above the 2001–2010 mean, while the temperature remained at the average level. April was accompanied by high soil moisture (close to field water capacity (FWC), pF = 2.0). By June, the moisture reserves had decreased, dipping below DPC for a short time (drought period capacity, pF = 2.85), but then increased after high rainfall in July and remained stable until the end of the growing season.

In 2018, the annual rainfall amounted to 71% (−106 mm) of the decade average. The annual temperature was 1.5 °C higher, rising to 2.2 °C during the growing season (indicating intensive evapotranspiration). This is slightly below the FWC (moisture reserves were only noted at the beginning of the growing season). By June, humidity had decreased almost to PWP (permanent wilting point at pF = 4.2). In July, after torrential rainfall, there was a short-term, pronounced increase in reserves (above DPC), and from August (precipitation 14% of the average, temperature of +2.6 ° C) until the end of the measurement period, the inventory fell again to a level close to the PWP.

In 2019, rainfall amounted to 95% (−19 mm) of the 2001–2010 average, while the annual temperature was 0.6 °C higher, which even rose to 3.7 °C in June (very high evapotranspiration). The highest (near FWC) moisture reserves were recorded in May after heavy rainfall. From June until the end of July, the reserves fell again to just above the PWP. After heavy rainfall in August, there was a noticeable increase in the reserves (close to the FWC), which continued on a slight upward trend until the end of the measurement period.

Analyzing the impact of the immediate environment on the results obtained, it can be concluded that the facilities as a whole are in of themselves roof buffers. At the same time, the roofs, at least abiotically (in terms of soil, and humidity), are independent of the rest of the building. Effective atmospheric precipitation (reaching the soil) and evapotranspiration predominately influence changes in soil retention.

3.3. Floristic Characterization of the Green Roofs with Reference to Habitat Conditions

The green roofs of military facilities are artificial habitats of anthropogenic origin, so they host synanthropic flora. After 100 years of functioning, forest communities with layers developed on each shelter (S 1-3). The list of recorded vascular plant species is presented in Table 4, along with their population abundances and ecological indicator values. In all phytocenoses, the dominant element of the tree layer was *Robinia pseudoacacia*. The regular pattern of individual specimens of this species implies that their juveniles were planted there, shortly after the shelters were constructed. *R. pseudoacacia* is a North American species with invasive traits. Subdominants include *Quercus robur* and *Acer platanoides*, which are native elements of deciduous forest communities. The shrub layers mainly consist of native species from deciduous forest and shrub communities that most likely settled there in a process of spontaneous succession. However, invasive *Padus serotina* is largely prevalent, and specimens of ornamental plants can also be found. In these layers, the juvenile stages of tree layer species are present. The herb layer vegetation differs in composition, as it developed under the tree canopy or in the canopy gaps. Under the tree canopy, tree seedlings dominate in the phytocenoses on all shelters. In the case of S-1, this stratum consists of the smallest number of the herbaceous plants, particularly in the canopy gaps, where only *Stellaria media* occurs with very small abundance. The herbaceous vegetation of S-2 and S-3 is richer and consists of hornbeam-oak forest species under the canopy, while species of ruderal and meadow communities occur in the gaps. Among the herbs, invasive *Impatiens parviflora* is present on each shelter, and this species is subdominant for S-1 and S-2.

Analysis of ecological indicator values showed that the vast majority of species from all the green roofs prefer fresh and moist soils, although the dominant *R. pseudoacacia* has the lowest moisture requirements and can even tolerate dry soils. Of all the shelters, the phytocenosis on S-2 has the highest share of species (i.e., shrubs and herbs from the canopy gaps) that can grow in dry soil conditions. This fact correlates with the deepest depletion of soil moisture resources disclosed in the soil on this shelter. In all communities, species of rich (eutrophic) soils dominate. Among the trees and shrubs, there are only a few species that can grow in moderately poor (mesotrophic) soils. Likewise, the indicator species of soils with a high humus and nitrogen content, for instance, *Chelidonium majus* and *Alliaria petiolata* also occur in all communities. These indicate the relatively high fertility of all the habitats, which results both from the depth of the plant litter and the humus horizons as well as the moder-mull type of forest humus, which is slightly acidic. The majority of species growing on all the roofs prefer neutral soils (pH 6.0–7.0), although some can grow in alkaline or moderately acidic soils. This corresponds with the results obtained for the plant litter pH. In all communities, species that prefer half shade and moderate light dominate, but plants that prefer full light conditions are well represented among the herbs growing in the canopy gaps. The light conditions (shade or light) strongly determine the differences in the occurrence of forest species relative to segetal/ruderal and meadow species in the herb layers.

Table 4. The list of species found on the three shelter roofs with their population abundances and ecological indicator values. Abundance is indicated according to the following scale: +—very few individuals, 1—a few individuals or clumps, 2—frequent but not dominant, 3—dominant or co-dominant. The ecological indicators are as follows: W—soil moisture, 2—dry, 3—fresh, 4—moist, 5—wet; Tr—trophy, 3—mesotrophic, 4—eutrophic, 5—very rich soil; R—acidity 2—acidic, 3—moderately acidic, 4—neutral, 5—alkaline; L—light, 2—moderate shade, 3—half shade, 4—moderate light, 5—full light; *—no data.

Species	**Shelter**			**Ecological Indicator**			
	1	**2**	**3**	**W**	**Tr**	**R**	**L**
Tree layer							
Populus alba L. dead	+			3-4	4	5	4
Quercus robur L.	+	+	+	3-4	3-4	3-4	4
Robinia pseudoacacia L.	1	3	2	2-3	3	3-5	4
Acer platanoides L.	3	3	2	3	3-4	4	4
Acer pseudoplatanus L.			2	3/4	4	3-5	3
Tilia cordata Miller			1	3	4-3	4-3	3
Tilia platyphyllos Scop.	+			3	4	5-4	3
Shrub layer							
Populus tremula L. juveniles	+	+		3	3	3	3
Quercus robur L. juveniles			1	3-4	3-4	3-4	4
Ulmus minor Miller juveniles	+	1		2-4	4	4	3
Crategus laevigata (Poir.) DC.		1	2	3-4	3-5	4-5	4-5
Crategus monogyna Jacq.		+		3-4	3-5	3-5	3-5
Padus avium Mill.		2		4	4	4-5	3
Padus serotina (Ehrh.) J.Agardh juveniles	1	2	1	3	3	3-4	3-4
Rosa canina L. dead		+		3-4	3-5	3-4	4-5
Rubus plicatus W. et N.		2	2	3-4	3	2-4	4-5
Robinia pseudoacacia L. juveniles			1	2-3	3	3-5	4
Acer platanoides L. juveniles	+	+	+	3	3-4	4	4
Acer pseudoplatanus L. juveniles			1	3/4	4	3-5	3
Cornus mas L.		1		*	*	*	*
Syringa vulgaris L.			+	*	*	*	*

Table 4. *Cont.*

Species	Shelter			Ecological Indicator			
	1	2	3	W	Tr	R	L
Sambucus nigra L.	2	1		3-4	4-5	4	(5)4-3
Sympharicarpos albus (L.) Blake		+		*	*	*	*
Liana							
Humulus lupulus L.			+	4-5	4-5	4-5	3
Parthenocissus quinquaefolia (L.) Planchon	+	2		*	*	*	*
Herb layer under the tree canopy							
Quercus robur L. seedings		3	2	3-4	3-4	3-4	4
Ulmus minor Miller seedlings		1		2-4	4	4	3
Chelidonium majus L.	2	1	1	3	4-5	4-5	3-4
Alliaria petiolata (Bieb.) Cav. et Grande	1	1	1	3/4	5	4	3
Crataegus monogyna Jacq seedlings	1			3-4	3-5	3-5	3-5
Geum urbanum l.			2	3-4	3-4	4-5	2-3
Padus serotina (Ehrh.) J. Agardh seedlings	1	2		3	3	3-4	3-4
Robinia pseudoacacia L. seedlings	2	2		2-3	3	3-5	4
Acer platanoides L. seedlings	3	2	1	3	3-4	4	4
Acer pseudoplatanus L. seedlings			1	3/4	4	3-5	3
Impatiens noli-tangere L.			1	4	4	4-5	2-3
Impatiens parviflora DC.	2	2	1	3	4	4	4-2
Tilia cordata Miller seedlings			1	3	4-3	4-3	3
Viola reichenbachiana Jord. ex Boreau		1	1	3	4-3	4-3	2-3
Lamium album L.			2	3	4	4	5-4
Sambucus nigra L. seedlings	2			3-4	4-5	4	(5)4-3
Dactylis polygama Horv.		2	2	3	3-4	4	3
Deschampsia cespitosa (L.) P.B.		2	1	4	3-4	3-4	3-5
Poa nemoralis l.		1		2-3	3	4-5	3
Herb layer in canopy gaps							
Urtica dioica L.		+	+	3-4	4-5	4	2-5
Fallopia dumetorum (L.) Holub		1	1	3	4	3-4	3
Rumex obtusifolius L.			+	3-4	4-5	3-5	3-5
Chenopodium album L.		+		3	4-5	4	5
Stellaria media (L.) Vill.	+		+	3-4	4-5	4	5
Geranium robertianum L.			1	3	3-4	4	2-3
Galium aparine L.			2	4-3	4-5	4	5-4
Ballota nigra L.		1		3	4-5	4	4
Galeopsis pubescens Besser			1	3-4	4-5	3-4	4
Conyza canadensis (L.) Cronq		1		2-3	3	3-4	5
Erigeron acris L.		1		2	3	4-5	5
Solidago gigantea Aiton		1	1	3-4	4		4-5

Table 4. *Cont.*

Species	Shelter			Ecological Indicator			
	1	2	3	W	Tr	R	L
Arrhenatherum elatius (L.) P.B. ex J. et C.Presl			3	3	4	4-5	4
Bromus inermis L.		2		2-3	3	4-5	5
Bromus sterylis L.			2	2	3	4	5
Dactylis glomerata L.		1		3	4-5	4-5	4
Festuca arundinacea Schreber		2		3-4	4	4	4
Poa pratensis L.		2	3	3	4	4	4
Poa trivialis L.			2	4	4	4	4
Total number of species	19	32	31				

4. Discussion and Data Limitations

The research on green roofs was conducted on the basis of regular observations on the shelters. Laboratory tests formed an essential complementary element. This is particularly important when protecting historic fortifications in situ where, as a result of many years of negligence and natural succession processes, the green roofs have changed over time. The exploratory nature of the research presented here has an advantage over studies carried out under controlled conditions on green roof models on a reduced scale. Field studies also provide an opportunity to confront the collected fragmented and not numerous archived documentation (e.g., drawings and aerial pictures) with the current facts. Due to the long period of operation (over 100 years), this documentation is often outdated. In addition, the adopted observation period, as well as the number of roofs tested, enabled observation of the periods of change occurring after different rain events in existing soil conditions with diverse vegetation scenarios. Furthermore, technical limitations precluded monitoring the microclimate directly at the facilities, but the research relied on data from a meteorological station located in the suburbs of Wroclaw, representative of the roofs studied. We are aware that such data would be extremely useful. Despite these limitations, some valuable results were obtained because very rarely have HF-related facilities been the subject of interdisciplinary environmental research.

It should be noted that the thickness of the levels on the green roofs depends mainly on how the builders covered them. Over time, this thickness may change as a result of vegetation growing via the accumulation of dead organic matter. Sometimes the thickness of the levels changes as a result of modernization work conducted on the shelters. Sometimes, as a result, various artefacts may appear in the soil. Some of these items were revealed during the research, e.g., crushed brick and slag, which are examples of frequently used mineral admixtures in soil substrates of artificial soil formations [54].

In turn, rainwater retention is one of the main functions currently fulfilled by green roofs in urban areas. The annual retention rate of green roofs can range between 5% and 85% of the precipitation [55–57]. The designs of the green roof are not the only factor influencing the formation of hydrological conditions [58–60], where time distribution and precipitation intensity [61–63], climatic conditions and seasonality [64], and pre-precipitation conditions [58], as well as the roof slope [65] also play an important role, [66]. What can also affect the amount of retention on green roofs are the initial conditions before precipitation, i.e., an antecedent dry period as well as the humidity of the substrate before precipitation [67–69]. Seasonal differences in green roof water retention are caused by varied evapotranspiration [70–72]. Higher evapotranspiration in warmer seasons causes faster drying and increased retention than in colder seasons [64,67,72]. In addition, local environmental conditions, construction techniques, and proper operation significantly determine the functionality and effects of green roofs that may influence, inter alia, the water cycle in an urbanized drainage basin [73–75].

Many of the currently conducted experiments concern small models with substrates with a thickness of several centimeters (extensive roofs), whose disadvantage is lower retention capacity and faster drying compared to intensive roofs [76]. The comparison of the results of these experiments with the tested roofs in HF areas is not fully reliable. There is a lack of literature on the study of comparable areas. On the basis of the literature of the green roofs in general, one can state that the retention capacity of systems increases along with an increase in the thickness of substrate layers. A study by Liesecke [77] demonstrated that with a substrate thickness of 4 cm that a green roof retained up to 45% of the annual runoff, and when the substrate thickness was increased to 10–15 cm, this led to a relatively small increase in retention of up to 60%. Scholz-Barth [78] demonstrated that with a 6-cm substrate layer that it is possible to retain 50% of rainwater, which rises to nearly 92% with an 11-cm layer. However, Fassman-Beck and Voyde [79,80], on the basis of measurements in profiles of 50 and 70 mm, did not find any significant differences in the retention of precipitation waters. Other studies that considered not only the thickness of substrates, but also the physical properties of the substrates, showed that the latter significantly impacts an enhanced capacity for water retention [21,81]. Generally, together with increase of substrate thickness, there was an increase in the retention capacity of soils [82,83].

The general characteristics of changes in the soil moisture content of green roofs during the analyzed vegetation periods of 2017–2019 are mainly dependent on the course of the precipitation. The rainfall distribution was highly uneven during the period under study. This meant, among other phenomena, sudden, momentary increases in water resources after torrential rainfall in July 2017 and 2018. Nevertheless, despite the occurrence of these phenomena on several occasions, no harmful excess of water was discovered in the profiles of green roofs. Due to the low retention capacity of the soils, the water resources easily available to plants (pF 2.0–2-85) tend to be depleted [76]. Only in 2017, which featured high rainfall, did soil water storage remain within the level of an easily available resource for the majority of the growing season. In the remaining two years, there were long-term soil moisture deficits, especially in the dry year of 2018 when periods of water storage were observed to be approaching a level that was unavailable to plants (DPC: pF = 4.2).

The retention potential of the studied soil formations can be assessed by comparing the measured water resources with the maximum amount of water that can be temporarily absorbed by the soil without endangering vegetation with an oxygen deficit. It is assumed that the amount of soil air should not fall below 10–15% of full water capacity (FWC). It follows that, relative to the measured average water resources, the soils on shelters S-1 and S-2 can temporarily cope with atmospheric precipitation in the region of 150 mm, while shelter profile S-3 can take about 100 mm. Therefore, the tested soils are capable of absorbing precipitation and, thanks to the construction of the entire structure, excess water is effectively drained.

Common knowledge dictates that roof conditions pose a challenge to the survival and growth of plants [59], particularly when it comes to moisture stress and severe drought. It is worth underlining that the green roofs located on historical shelters are only a few meters above ground level, which is why they are not as exposed to harsh conditions as in the case of tall buildings located, for example, in city centers. Similarly, the trees growing in the vicinity shade the ground and limit evaporation, while the root mass of the combined vegetation prevents physical substrate damage caused by wind and severe rainfall. On the other hand, the most shaded S-1 roof has the poorest soil and species composition. Aspects related to sunlight require additional research, as they may significantly influence the water balance. Historically, the S-1 and S-2 roofs were the sunniest, while S-3 was partially shaded from the beginning, which is reflected in the intensity of evapotranspiration and may affect the soil water balance. The aspect of the proportion of sunny-shady areas and the vegetation layers requires further research.

In all three green roofs, the organic matter in the roof soil retains moisture and helps provide the vegetation with nutrients, while also buffering against pH change [84]. It seems that the best conditions for plant development prevail on green roofs S-2 and S-3 due to the occurrence of clay in the soil formations, which ensures the vegetation has a superior water supply, as reflected in the higher total number of species, especially in the herb layer, inhabiting them in relation to S-1.

Despite the water shortages that occur during the growing season in green roof soils, their vegetation is able to grow properly and create forest communities with typical layers. However, the intensification of droughts and the increase in temperature during the growing season in the future may lead to the gradual loss of species that are most sensitive to water shortages. Research carried out after these edifices had been in operation for more than 100 years revealed that the green roofs there, despite their simple construction, function well in terms of benefiting the entire building as well as the development of vegetation and water management of the area. The negligence of procedures usually applied in urban green areas (raking leaves, mowing the undergrowth causing, inter alia, the destruction of tree and shrub seedlings, forming and illuminating crowns, the use of herbicides, etc.) caused the accumulation of an organic-rich horizon layer, which promotes the spontaneous development of vegetation along the path of natural succession as well as settlement of the area by species well adapted to the conditions of the habitat.

During the course of the study, it was not possible to determine whether local material from the shelter construction period was used for the construction of green roof soils. In addition, extensive investigations only yielded incomplete archival documentation and inventory drawings of the shelters and their green roofs. Therefore, more detailed research is required in the future, including a large number of sites, more data, and frequent long-term investigations.

To summarize, HF protection transcends conservation issues and is important not only for historical and educational values, but also in terms of nature. It can provide an opportunity for a better understanding of historical buildings that can be treated as an important "reservoir" of past environmental data. Studies of historic green roofs on historic fortifications can provide a lot of valuable information about how these engineering structures have functioned over the years. Historical green roofs provide not only a material link with the past, but also a "connection with the future." For over a century, they have proven their effectiveness and endurance, being not only an example of sustainable green roofs, but also, and perhaps above all, indicating a possible direction in how to shape proven forms of green roofs in an era of progressing climate change.

In consequence, all future protection and development scenarios for HF facilities, including restoration techniques, should be designed not only on the basis of a potential increase in anthropopressure resulting, for example, from growing tourist traffic, but also updated as climate scenarios evolve. They should also be based on existing strategic documents related to the preservation of urban biodiversity or climate protection.

5. Summary and Conclusions

- Green roofs created on fortifications in operation for over 100 years currently play an important role in city peripherals by improving storm water quality, reducing the rate and volume of runoff, mitigating the urban island heat effect, and supporting wildlife and habitat biodiversity, as well as carbon sequestration, and providing urban dwellers with the educational benefits of small-scale ecosystems. As "wild green roofs" on ageing shelters, they constitute a place of refuge for native forest plant species and for species biodiversity and are a valuable element of the system of ecological panels and corridors.
- In order to preserve their natural values, one should limit anthropopression, which is understood as actions aimed at transforming these sustainable ecosystems.
- Protective measures should be taken to care for the vegetation and soil environment of green roofs, especially the surface horizon of the soil in which the accumulation of organic matter occurs alongside the accumulation of nutrients for plants and water retention.
- The protective measures should especially include:
    - Keeping the roof area off limits (to pedestrian traffic) as far as possible, as it was during the military use of the buildings, in order to prevent damage to the soil litter;

- Preservation of the herb and shrub layer containing, inter alia, juvenile tree stages, which enables natural renewal of the tree stand;
- Care must be taken to protect soil organisms responsible for the breakdown of organic matter, eliminating invasive species, especially *Padus serotina* and monitoring their settlement on green roofs;
- When repairing and maintaining flat roofs, the original soil should be re-used, avoiding fertilization and the introduction of new species, especially ornamental plants. This would favor the preservation of genius loci, combining historical, cultural, and natural values, constituting an interesting complement to the "blue-green infrastructure" of the city.

Author Contributions: Conceptualization, Ł.P. and T.K.; methodology, Ł.P., T.K., A.B., D.K.; software, Ł.P.; investigation, Ł.P., T.K., A.B., D.K.; resources, T.K., A.B.; data curation, Ł.P., A.B.; writing original draft preparation, Ł.P.; writing—review and editing, Ł.P., D.K.; visualization, Ł.P., T.K.; supervision, T.K., D.K., A.B.; project administration, Ł.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: We would like to thank the Provincial Office of Monument Preservation and the Municipal Conservation Office in Wrocław for support in this research. This project was prepared without any external foundlings or grant. The work uses meteorological data from the Wroclaw–Swojec Faculty of Agrometeorology and Hydrometeorology Observatory (WOAiHW-S), cartographic materials from the Staatsbibliothek zu Berlin–Preussischer Kulturbesitz, and aerial photos from the state archives in Wrocław. We would also like to thank the three anonymous reviewers for their comments and suggestions, Katarzyna Pałubska and Marcin Górski for their professional consultation, Steven Jones for translating this paper, and Max Kooij for correcting this paper.

Conflicts of Interest: The authors declare no conflict of interest.

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