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A database of global wetland validation samples for wetland mapping

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Abstract A database of global wetland validation samples (GWVS) is the foundation for wetland mapping on a global scale. In this work, a database of GWVS was created based on 25 "wetland-related" keyword searches of a total of 3,506 full-text documents downloaded from the Web of Science. Eight hundred and three samples from a total of 68 countries and 141 protected areas were recorded by the GWVS, including samples of marine/coastal wetlands, inland wetlands and human-made wetlands, at ratios of 53 %, 41 % and 6 %, respectively. The results exhibit spatial distribution among Terrestrial Ecoregions of the World, the World Database on Protected Areas and the Database of Global Administrative Areas. Within most of the biomes, protected areas and countries examined, the very low concentration of samples requires more attention in the future. The greatest concentration of samples within a single biome is found in the tropical and subtropical moist broadleaf forest biome, accounting for 27 % of the total samples, while no sample is found in the biome of tropical and subtropical coniferous woodland. Greater efforts are expected to be made to record samples in Oceania, Central Europe, Northern Europe, Northern Africa, Central Africa, Central America, the Caribbean, and midwestern South America. Our data show that it is feasible to map global wetlands using Landsat TM/ETM+ at 30-m resolution. The continued improvement of the GWVS sharing platform should be reinforced in the future, making a strong contribution to global wetland mapping and monitoring.

Keywords GWVS · Remote sensing · Wetland mapping · Wetland monitoring · Protected area

1 Introduction

As of August 2014, more than 2,187 wetlands have been designated as Wetlands of International Importance, covering a total area of 208.6 Mha (Ramsar, 2014). The products of global wetlands are the foundation of wetland research, management and conservation. They play a critical role in studies of habitat and biodiversity [1–4], carbon cycling [5–8] and public health [9, 10]. They are also essential in improving the performance of ecosystem, hydrological and atmospheric models [11]. The extent and distribution of global wetlands need to be determined first.

Remote sensing has proven to be a useful technique for monitoring the components of the global surface [12–14] and has a high application potential for wetlands [15, 16]. The European Space Agency, in collaboration with the Ramsar

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Secretariat, launched the GlobWetland project in 2003, and the overall objective of GlobWetland was to facilitate the integration of remote sensing techniques into the conservation and management of wetlands [17]. Although the capabilities of remote sensing in terms of spatial, temporal and spectral resolution is increasing, an reliable and affordable global wetland map is still not derived from remote sensing with high resolution and complete categories. The only current wetland maps at a global scale were extracted from several types of global land cover maps derived from remote sensed data at 1 km and 300 m scales [18].

However, the methods by which wetlands have been identified or classified using global datasets have varied, and the results have often been incompatible or inconsistent [19]. The global mean per-pixel agreement measured with class-specific consistency is high for open water and low for wetlands [14]. Areas classified as wetlands in a pixel in one dataset are rarely classified as wetlands in the same pixel in the other datasets [18]. Although Envisat ASAR Global Monitoring Image Mode Product (GM) is capable of capturing not only the extent but also the dynamics of wetland areas, a global wetland map has not been made by GM at 1-km resolution [15]. The current wetland mapping products on a global scale such as Global Lake and Wetland Database (GLWD) and the Ramsar site database cannot match either the need for global wetland dynamic monitoring or the need for understanding their internal processes.

After the first set of wetland maps of China derived from Landsat and CBERS-02B, images between 1978 and 2008 were produced [20], and a synergistic approach with census and spatially explicit datasets was used to create a 1-km wetland map for China [21], a finer resolution (30 m) observation and monitoring of global land cover was then produced in China [14]. Zhao et al. [22] built a global validation dataset based on interpreting Landsat TM/ETM+ images and other high-resolution imagery from Google Earth for a total of 38,644 predetermined sample locations with a systematic unaligned sampling scheme. Further research is necessary to build a database of global wetland validation samples (GWVS) including more comprehensive wetland types that can benefit from wetland mapping derived from remote sensing on a global scale.

Three ways to validate samples are shown as: (1) image acquisition; (2) field investigation; and (3) data from a third party. The interpretation of wetlands derived from remote sensing images and developed by an automatic classification method should be based on components and texture features such as vegetation, hydromorphic soil and hydrology. In this paper, we establish the preliminary database of GWVS from the Web of Science by searching for wetland-related keywords, which benefits global wetland mapping and monitoring.

2 Constructing a global validation dataset: data and methods

2.1 Data and classification scheme

The articles for the study were downloaded from the Web of Science. The keywords for wetland-related searches are shown in Table S1. A total of 40,449 documents were found from the Web of Science between January 2008 and July 2012, and only 3,506 full-text documents were downloaded for sampling. The definitions of wetland are still a debatable issue [23, 24], and more than 60 definitions of wetlands are found in the world. However, there is still no widely accepted classification for wetlands with scientific significance on a global scale. Fortunately, the wetland classification of the Ramsar Convention has played an important role in wetland management on a global scale, and the most significant aspect is that category I of the Ramsar wetland classification system is widely approved for wetland classification. However, category II of the Ramsar classification system includes some generalised wetland types and overly specific types. The Ramsar marine/coastal wetlands of type (D, E, G) and type (J and K) have been merged into coastal mudflats and lagoons in GWVS, respectively (Table S2). The Ramsar inland wetlands of type (W and Xf), type (Sp, Ss, Tp, Ts and R), type (Y and Zg), type (M and N), type (O, P and Q) and type (U and Xp) have been merged into swamp, marsh, spring, river, lake and peatland, respectively. Ramsar human-made wetlands of type (2 and 6), type (1 and 5) have been merged into water storage areas and salt field/fish farm, respectively (Table S2).

2.2 Sampling and interpretation

The information “Author”, “Published time”, “Title” and “Journal” of wetland-related papers was converted from “.enl” to “.xls” in EndNote X4 Software, and “ID”, “Organisation of first author”, “Country”, “Site name”, “Survey time”, “Latitude”, “Longitude”, “Elevation”, “Area_ha”, “Wetland type”, “Overview”, “Physical features”, “Ecological features”, “Verified”, “Dimension of sample (m)”,“The year of high resolution imagery in Google Earth”, “Image clear or not” and “Remarks” was added to the database header. The information of central coordinate was changed into the same degree mode by using the mid functions (correct to 7 decimal places). Take the functions as an example:

$$\begin{aligned} \mathrm{N}29^{\circ}14'45'' &= \mathrm{MID}(\mathrm{A1},2,2)+\mathrm{MID}\ (\mathrm{A1},5,2)/60 \\ &\quad + \mathrm{MID}(\mathrm{A1},8,2)/3600 \\ &= 29.2458333, \end{aligned} \tag{1}$$

$$\begin{aligned}\mathrm{E}102^{\circ}45'25'' &= \mathrm{MID}(\mathrm{B}1,2,3)+\mathrm{MID}(\mathrm{B}1,6,2)\\ &\quad +\mathrm{MID}(\mathrm{B}1,9,2)/3600\\ &= 102.7569444. \end{aligned} \tag{2}$$

Initially, 3,682 samples with geographic information were found. These samples were checked in ".shp" using the database of Global Administrative Areas (GADM_V2, downloaded from http://www.gadm.org/). Many unrelated geographic information was found in these articles, so much so that some samples were outside their continents or countries. Minus sign indicates west of prime meridian in longitude and south of equator in latitude. If the description of a sample was record in the northern hemisphere, while the geographic information showed the wrong sign, the sample was considered as an incorrected sample. After checking, only 2,784 samples were left. And then, the high spatial resolution images from Google Earth were used to check these samples one by one, and the time of the imagery was recorded. Finally, only 803 samples were considered correct after further judgment.

In most cases, the homogeneous area is relatively uniform, repetitive and simple in texture, so a texture analysis approach was adopted [22]. We assumed that the dimensions of the sample could be measured from high-resolution imagery in Google Earth by the ruler according to a pure-pixel selection in which the range of the surface is homogenisation. The dimensions of incircle were adopted to record the dimensions of sample, although many of these features are surely not circular or quasi-circular in shape.

The "Twin Cays mangrove sample" was a sample of mangrove [25]. Its latitude coordinate and longitude coordinate were 16.8326380 N and 88.1004230 W. Its dimension is 76 m. Twin Cays is a 92-ha archipelago located 12 km offshore of the coast of Belize in Central America (recorded in "Overview"). Twin Cays has limited terrestrial influence and is constantly flushed by ocean water. There are two seasons: a wet season from July to October with an average rainfall of 218 cm per year and a dry season from November to the next June (recorded in "Physical features"). The island substrate is principally peat formed from the fine roots of mangrove trees, primarily from the dominant species Rhizophora mangle. The study area is located in the interior zone of the mangrove forest, which covers approximately 60 % of the mangrove ecosystem in Twin Cays and where dwarf trees (1.5 m tall) are found (recorded in "Ecological features"). According to Table S2, the mangrove sample was classified as a coastal swamp.

2.3 Evaluation of the accuracy of GLWD-3

GLWD focuses on three coordinated levels [26]. GLWD-1 comprises the 3,067 largest lakes (area $\geq$50 km^2) and 654 largest reservoirs (storage capacity $\geq$0.5 km^3) worldwide. GLWD-2 comprises permanent open water bodies (lakes, reservoirs and rivers) with a surface area $\geq$0.1 km^2 excluding the water bodies contained in GLWD-1. GLWD-3 comprises lakes, reservoirs, rivers and different wetland types in the form of a global raster map at 30-s resolution. For GLWD-3, the polygons of GLWD-1 and GLWD-2 were combined with additional information on the maximum extents and types of wetlands. The "lake" class in both GLWD-2 and GLWD-3 also includes human-made reservoirs because only the largest reservoirs have been distinguished from natural lakes. Information included in the generation of GLWD-3 consisted of DCW (Digital Chart of the World, hydrography layer, ESRI [27]), ArcWorld (ArcWorld 1:3 M, hydrography layer, ESRI [28]), WCMC (global wetlands map, WCMC [29]) and GLCC (Global Land Cover Characterisation, Loveland et al. [30], in "Global Ecosystem" classification).

In this paper, GLWD-3 was changed into ".shp" by the "Raster to Polygon" tool in ArcToolbox. "Intersect" was then used to check the consistency of GLWD-3 and GWVS. Table S3 was used to cross-match wetland types between GWVS and GLWD-3. If the wetland types in GLWD-3 are almost the same or similar to the wetland types in GWVS (with a buffer = 500 m or without buffer), they are considered to be the correct samples.

The formula of user accuracy evaluation is shown as

$$a = b/(b+c), \tag{3}$$

where a is user accuracy, b is the number of correct samples, and c is the number of misclassified samples.

3 Characteristics and application of the dataset: results

3.1 Quantity and distribution of GWVS

A total of 803 samples are found in GWVS; the number of subtypes and samples of marine/coastal wetlands, inland wetlands and human-made wetlands is 6 and 424, 7 and 329, 2 and 50, respectively.

The greatest proportion of samples is estuary and coastal swamp, which are 125 and 107 samples, respectively. The lowest proportion is the wetland subtype consisting of mudflats and salt fields/fish farms, where the numbers are only 9 and 11, respectively. The distribution of GWVS across the WWF biomes is displayed in Fig. 1. The greatest concentration of GWVS within a single biome is found in the tropical and subtropical moist broadleaf forest biome (26.5 %) and in the temperate mixed broadleaf forest biome (13.6 %). Samples of estuary, coastal swamp and river are generally located within the temperate mixed broadleaf forest, mangrove and tropical and subtropical moist broadleaf forest biomes, respectively.

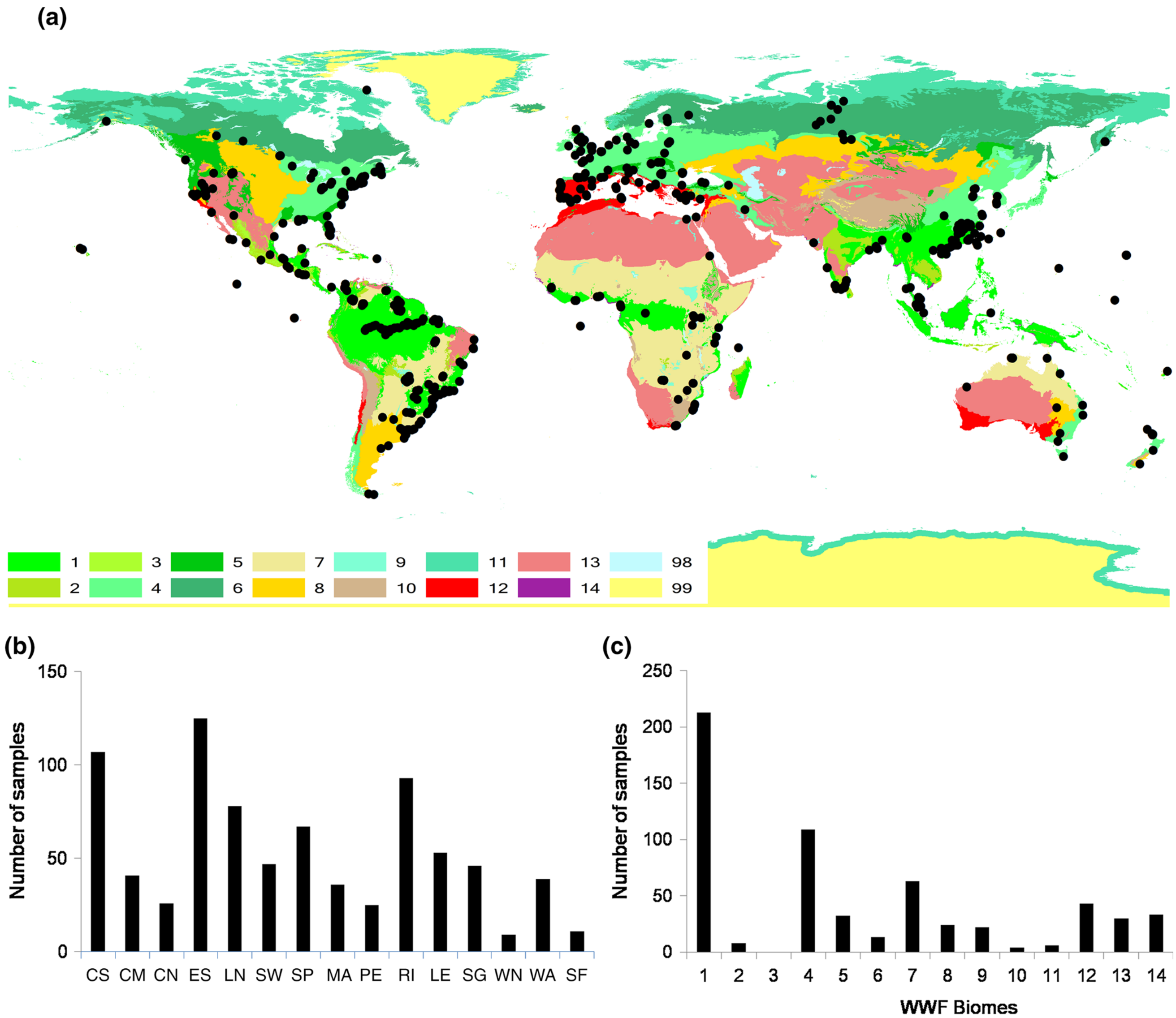

Fig. 1 Global wetland validation samples across WWF Terrestrial Biomes. **a** Distribution of samples across WWF Biomes. **b** Number of samples among types. **c** Number of samples across WWF Biomes. 1: Tropical, subtropical moist broadleaf forest; 2: Tropical, subtropical dry broadleaf forest; 3: Tropical, subtropical coniferous woodland; 4: Temperate mixed broadleaf forest; 5: Temperate coniferous woodland; 6: Boreal forest/taiga; 7: Tropical and subtropical grassland savanna/shrubland; 8: Temperate grassland savanna and shrubland; 9: Flooded grassland; 10: Montane grass/shrubland; 11: Tundra; 12: Mediterranean forest wood/shrubland; 13: Desert and xeric shrubland; 14: Mangrove; 98: Lakes; 99: Rock and ices. CS: Coastal swamp; CM: Coastal marsh; CN: Coastal nudation; ES: Estuary; LN: Lagoon; SW: Shallow water; SP: Swamp; MA: Marsh; PE: Peatland; RI: River; LE: Lake; SG: Spring; WN: Wet inundation; WA: Water storage area; SF: Salt field and fish farm

A total of 68 countries are found in GWVS, accounting for <30 % of all countries in the world. There are still no samples in 157 countries /regions, and more work should be performed in the future.

3.2 Dimensions of the validation sample

Sample size plays an important role in wetland mapping on a global scale, and the dimensions of the samples were obtained from the homogeneity characteristics of the same wetland patch. Landsat images and MODIS images with spatial resolutions of 30 and 500 m are two of the most important data sources for global wetland mapping and monitoring [14]. Therefore, a sample with dimensions ≥500 m would be considered a large sample. If the sample dimensions are ≤30 m, it is a small sample. When the sample dimension is between 30 and 500 m, it is a medium sample. The ratio of large, medium and small samples is 27 %, 58 % and 15 %, respectively. Figure 2 shows the maximum and average sample dimensions.

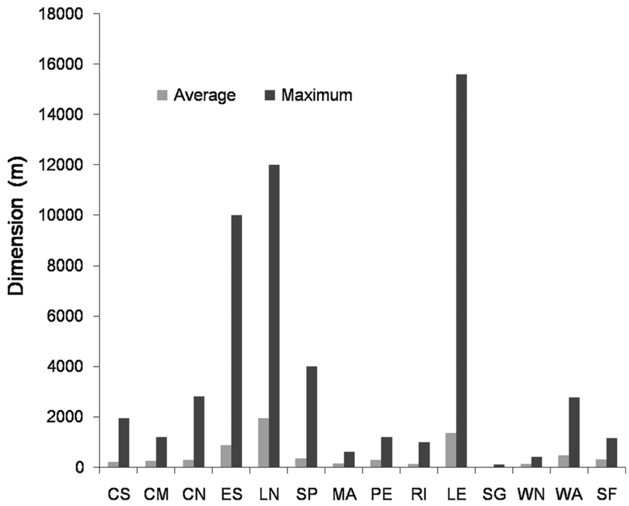

Fig. 2 Dimension of sample. CS: Coastal swamp; CM: Coastal marsh; CN: Coastal nudation; ES: Estuary; LN: Lagoon; SP: Swamp; MA: Marsh; PE: Peatland; RI: River; LE: Lake; SG: Spring; WN: Wet inundation; WA: Water storage area; SF: Salt field and fish farm

3.3 EVI characterisation of the samples

The 16-day MODIS composite Enhanced Vegetation Index (EVI) time series with 250-m spatial resolution (MOD13Q1 product, downloaded from http://modis.gsfc.nasa.gov/data) for 2008–2011 was extracted at the sample locations. The EVI is in the expected range from −2,000 to 10,000 with a fill value of −3,000, and its coefficient is 0.0001. Figure 3 would be used for mapping different wetland types in the future [22].

Affected by many factors, it is difficult to have high and reliable accuracy of wetland classification at the large scale by computer automatic classification. Coupling with multi-source remote sensing data and several automatic classification methods (e.g. object oriented and decision tree), spectral characteristic curves (e.g. EVI, etc.) will be used to build a algorithm of wetland automatic classification based on knowledged to solve the massive sample selection, to address issues such as change information identification and change pixel automatic classification.

3.4 Information cues for the management of protected area

The World Database on Protected Areas (WDPApol2013, downloaded from http://www.wdpa.org/) was overlaid to analyse the samples in the protected areas in the world. A total of 260 samples are found in 141 protected areas, accounting for 32 % of total samples and 0.1 % of the total protected areas, respectively.

Of the samples, 41 % were distributed in National Park (II), Protected Landscape/Seascape (V). Fifteen percentage of samples were found in Habitat/species Management Area (IV), Protected Area with sustainable use of natural resources (VI) and Strict Nature Reserve (Ia). Only one sample is found in Natural Monument or Feature (III) and no sample in Wilderness Area (Ib). Of samples, 44 % are without category information. More attention should be paid to wetland sampling in protected areas, where little information for wetland mapping and monitoring is found.

3.5 Assessment of GLWD-3 accuracy

A total of 296 samples in GWVS without buffer can be used to obtain the user accuracy of GLWD-3. A total of 39 complex wetland samples (type 10–12) and seven reservoir samples were considered to be absolutely correct samples. Lake and coastal wetland samples, 84 and 59, respectively, were most used to check the user accuracy of GLWD-3, and their user accuracy was 72.6 % and 94.9 %, respectively. The most noteworthy sample types were freshwater marsh and floodplain, and swamp forest and flooded forest, and their user accuracy was 50 % and 38.1 %. Overall, the total user accuracy of GLWD-3 was 73.3 %, and the user accuracy of water body (types 1–3) and marshland (types 4–5) was 71.2 % and 46.5 %, respectively.

When a buffer (diameter = 500 m) was added to the GWVS, the samples used to calculate the user accuracy of GLWD-3 increased to 437, and the total user accuracy changed minimally. Table S4 shows that the most number of 50 %–100 % wetland (type 10) is spring, and the number of samples and user accuracy are 22 % and 66.7 %. It is noteworthy that the user accuracy of freshwater marsh and floodplain increased from 50 % to 64.6 %, while that of swamp forest and flooded forest decreased slightly.

4 Conclusions

The analysis of papers presented at the Web of Science indicates that a credible foundation of research and development has been put in place over the last few years that can provide very useful and cost-effective tools to support the updating of the GWVS. This research contributes the first global wetland validation samples in terms of wetland remote sensing mapping on a global scale. The results exhibit spatial distribution among WWF Biomes, WDPA and GADM, and within most biomes, protected areas and countries examined, the low concentration of samples in GWVS needs to be given more attention in the future. Wetland types with only a few samples reflect our ignorance of them and the need for intensive research. This article

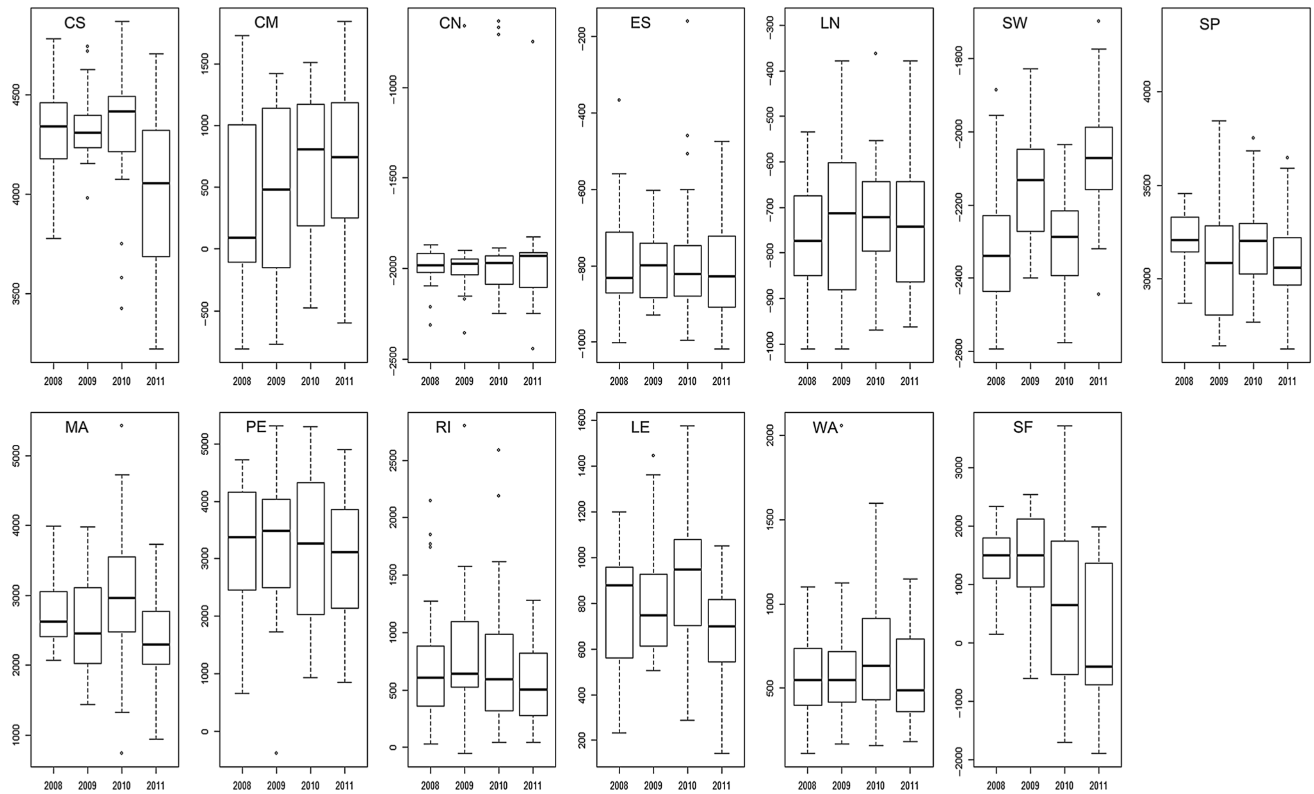

Fig. 3 EVI time series for samples of different wetland types (the dimension of sample is ≥500 m). CS: Coastal swamp; CM: Coastal marsh; CN: Coastal nudation; ES: Estuary; LN: Lagoon; SW: Shallow water; SP: Swamp; MA: Marsh; PE: Peatland; RI: River; LE: Lake; WA: Water storage area; SF: Salt field and fish farm

provides some inspiration for the management of global wetlands for international bodies such as the United Nations, Wetlands International, International Geosphere-Biosphere Program, the Group of Earth Observations, the Society of Wetland Scientists, World Wide Fund for Nature, The Nature Conservancy and Global Environment Facility, etc.

Wetlands vary seasonally and over years in their appearance and size—they are highly dynamic. Since the industrial revolution, wetlands are suffering serious interference under the dual influence of climate change and human disturbance. The data source of GLWD is quite old (before 2000, even 1992), and the user accuracy of marshland is unable to meet the needs of wetland monitoring and scientific research.

Some keywords like “riparian” and other hygrophytes were ignored in this paper. There are also some limitations to using Google Earth to check wetland samples, most notably peatland samples. In the future, not only the EVI curves but also other high-resolution imagery and spectral curves will be an important means of diagnosis. Operationalisation for the purpose of monitoring the dynamics of wetland extent, area change and wetland processes will require that future GWVS missions provide a consistent process over a series of time periods.

We shall propose a method of design and implementation of a GWVS sharing platform in the future, as well as standardisation construction, data updates and maintenance, tests and checks. Different data access methods will be added to the GWVS, such as image acquisition, field investigation and data from third parties. A volunteer system and data interchange institution within the sharing platform will be considered for the future. An extensive international cooperation and continued improvement of the GWVS sharing platform will be reinforced in the future and provide free basic data for the automatic extraction of global wetlands. Specifically, an overall and deep discussion of the cross-matching of wetland types between GWVS and the Ramsar classification system should be begun as soon as possible.

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Conflict of interest The authors declare that they have no conflict of interest.

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