

Geo-Wiki: An online platform for improving global land cover

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ABSTRACT

Land cover derived from remotely sensed products is an important input to a number of different global, regional and national scale applications including resource assessments and economic land use models. During the last decade three global land cover datasets have been created, i.e. the GLC-2000, MODIS and GlobCover, but comparison studies have shown that there are large spatial discrepancies between these three products. One of the reasons for these discrepancies is the lack of sufficient in-situ data for the development of these products. To address this issue, a crowdsourcing tool called Geo-Wiki has been developed. Geo-Wiki has two main aims: to increase the amount of in-situ land cover data available for training, calibration and validation, and to create a hybrid global land cover map that provides more accurate land cover information than any current individual product. This paper outlines the components that comprise Geo-Wiki and how they are integrated in the architectural design. An overview of the main functionality of Geo-Wiki is then provided along with the current usage statistics and the lessons learned to date, in particular the need to add a mechanism for feedback and interaction as part of community building, and the need to address issues of data quality. The tool is located at geo-wiki.org.

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1. Introduction

Global land cover is a key terrestrial baseline dataset that is used in a variety of different global, regional and national scale applications, e.g. resource assessments of forest and agricultural land, and as inputs to large scale economic land use and ecosystem models. In the last decade, three global land cover products have been developed: the GLC-2000 (Fritz et al., 2003), MODIS (Friedl et al., 2002) and GlobCover (Bicheron et al., 2008; Bontemps et al., 2011). Recent studies have shown that when these products are compared, there are significant amounts of spatial disagreement across land cover types, in particular in the cropland and forest domains even when taking semantic differences in the legend definitions into account (Fritz et al., 2010b; Fritz and See, 2008). The reasons for this disagreement include the use of different satellite sensors, different classification methodologies and the lack of sufficient in-situ data, which are needed to train, calibrate and validate land cover maps. This has a number of potentially wide reaching consequences. The first is uncertainty around how much land is currently under different land cover types such as forest or cropland. Accurate

estimates are needed to determine how much land is available for biofuels, for example, or where agricultural production could be expanded in the context of food security. Uncertainty in land cover is also propagated through modeling. When different land cover products were used in a vegetation model to estimate biomass, Quaipe et al. (2008) found that estimates of gross primary productivity varied over a range of $254 \text{ gC m}^{-2} \text{ a}^{-1}$ (or between -15.8% and 8.8% when expressed as a percentage difference), depending upon the land cover product used. Moreover, Fritz et al. (2010a) have shown that there is real monetary value in improving land cover information when considering different climate change mitigation options in a situation where it is not known if one land cover product is better than another.

Two significant developments have occurred in the last decade, which have the potential to vastly improve land cover products in the future. The first is the ubiquitous access to free high resolution satellite imagery through Google Earth, Yahoo and Bing. This imagery is a valuable resource that can be used to compare land cover products with what appears on the satellite imagery. For example, Biradar et al. (2009) used field plot data in the development of their global map of rainfed areas for class identification, labeling and accuracy assessment. Google Earth was used to provide 11,000 locations from high resolution imagery; 1861 data points were available from field campaigns; and a further 3982

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points were provided by the Degree Confluence project (<http://confluence.org/>), which collects photos and descriptions of the landscape at latitude longitude intersections. From this field plot data set, 1000 randomly sampled points from Google Earth and a further 915 points from field campaigns were used in the accuracy assessment of the map. Google Earth imagery was also one of many different sources of information used in the validation of GlobCover 2009 (Bontemps et al., 2011).

The second development is access to online mapping tools such as Google Map Maker (<http://www.google.com/mapmaker>) and Wikimapia (<http://www.google.com/mapmaker>), which are part of the Geographic World Wide Web (or GeoWeb). The GeoWeb has led to the emergence of neogeography (Haklay et al., 2008), which breaks away from traditional map making by professional cartographers and mapping agencies and places this capability in the hands of individuals who want to share geographical information online either in a social or information creation context (Turner, 2006). The sharing of any kind of information by citizens in a collective bottom-up approach can be generalized under the term crowdsourcing (Howe, 2008). Where there is a spatially explicit aspect to this content, it is referred to as 'volunteered geographic information' (VGI) whereby citizens act as environmental or social sensors (Goodchild, 2008). VGI and crowdsourcing are often used interchangeably although Goodchild argues that crowdsourcing entails a process of consensus or working toward a common goal that is not necessarily present in VGI where individuals provide information independently (Schurmann, 2009). However, the blurring of terms is understandable as individual, independent contributions may well produce a collective outcome that becomes part of a larger goal. The type of information provided by individuals can be textual or photographic, and there are now a multitude of examples of where users submit spatially referenced information to a website, e.g. Wikimapia (wikimapia.org), Openstreetmap (openstreetmap.org), MapAction (mapaction.org) and Panoramio (panoramio.com). Institutions such as the European Environment Agency have developed the site 'Eye on Earth' (www.eyeonearth.eu), which involves the wider public in monitoring the environment. This two-way communication platform brings together scientific information with feedback and environmental observations from millions of ordinary people. Other examples include the eBird project (Marris, 2010), which contains more than 48 million bird sightings entered online by the bird watching community, and Galaxy Zoo (Timmer, 2010), which involves the public in the classification of galaxies and has led to new discoveries and papers jointly authored by scientists and the public. A recent paper in Nature (Khatib et al., 2011) demonstrates the power of crowdsourcing in solving a retroviral protein structure through the Foldit game.

Although crowdsourcing initiatives are becoming increasingly more popular, crowdsourcing also has negative aspects. The issue of assessing the quality or credibility of crowdsourced data is one problematic area that has barely been examined (Flanagin and Metzger, 2008; Haklay et al., 2010). Flanagin and Metzger (2008) recognize that provision of a training element provides some credibility but the establishment of acceptable credibility measures is still lacking. One example in this direction would be the incorporation of a user rating system or what Haklay et al. (2008) refer to as social accounting tools, which would provide a collective mechanism to assign quality. Examples of this can already be found in Wikipedia with the use of coloured text to denote increasing levels of reputation and in Wikimapia where approval of information must be attained in order to remain on the site (Flanagin and Metzger, 2008). More systematic attempts to assess the quality of crowdsourced information have been undertaken with regards to OpenStreetMap (OSM) data (Haklay, 2010; Haklay et al., 2010). Positional accuracy was shown to be around 6 m with

good overlap between roads in OSM when compared to data from the UK Ordnance Survey. However, they also found poor instances of quality in their sample and they note that OSM do not have a user rating system for quality assurance at present (Haklay, 2010). Haklay et al. (2010) then tested Linus' Law on OSM data, i.e. is an increase in quality observed as the number of contributors increases? The results of their study showed that the law does apply to the positional accuracy of roads in OSM, with the first 5 contributors making the most difference to improvements in quality and flattening out at approximately 15 contributions. These initial studies highlight the need for more research on assessing quality and in developing mechanisms and metrics for determining reliability and trust of crowdsourced data.

Geo-Wiki, which was developed by Fritz et al. (2009), attempts to integrate open access to high resolution satellite imagery from Google Earth with crowd-sourcing into a single Web2.0 application as a way of vastly increasing the amount of information on land cover. This information can be used for training and for cross checking the calibration and validation of land cover products. For clarity, we subdivide validation into hard and soft validation. Hard validation involves the use of in-situ data collected on the ground for assessing the accuracy of a land cover product, and would generally be undertaken by remote sensing and land cover experts in the development of a land cover product. Soft validation, in this context, refers to the assessment of land cover maps using other tools such as Google Earth, geo-tagged photos, local knowledge, etc., which may be contributed by experts or the public.

Another aim of Geo-Wiki is to create hybrid land cover products. A hybrid product uses existing land cover maps as an input as well as consolidated crowdsourced data, where consolidated in this context means that quality assurance measures are in place. The combined information will be better than any individual product, which is the same principle under which data fusion and soft computing operates. Hybrid products will be available at spatial resolutions of 300 m, 500 m or 1 km² in the simplified legend of Herold et al. (2008), which was developed for comparison of different land cover maps and for the recalculation of accuracies. The legends were first mapped onto LCCS classifiers and then re-aggregated to a common set of 13 classes. The legends of the three land cover products in Geo-Wiki would map onto this simplified legend and would then be combined with the consolidated validation points to determine which land cover product is the most correct in which areas based on expert ranking and the crowd-sourced evidence.

The aim of this paper is to describe the Geo-Wiki application, in particular the components that comprise the system, how these components fit together into a single architecture, and the standards and protocols that have driven this design. An overview of the main functionality of Geo-Wiki is then provided along with statistics on the current usage and the lessons learned to date.

2. The design and architecture of Geo-Wiki

The design of Geo-Wiki follows the guidelines for the development of a standards-based geospatial portal as outlined by the Open Geospatial Consortium (OGC, 2004). This Geospatial Portal Reference Architecture is based upon the principles of Service Oriented Architecture (SOA), where services are discoverable on a network, facilitating data integration and interoperability (Erl, 2005). The Geospatial Portal Reference Architecture outlines four classes of service that are required in order to be OGC compliant: portal, portrayal, data and catalog services. Geo-wiki contains a portal service for system management and as a single entry point to the system. The portrayal service is implemented as a Web Map Service (WMS), which is used to display the geospatial

data as images on Google Earth. The data service consists of a Web Feature Service (WFS) for serving vector data and a Web Coverage Service (WCS) for serving raster data. Although implemented, these services are yet to be fully integrated into Geo-Wiki. The WFS will be used to serve the crowd-sourced data in vector format while the WCS will serve the hybrid map and disagreement maps in geo-tiff or another raster format. The Catalog Web Service (CWS) is a metadata portal which serves the metadata of all the products in Geo-Wiki and conforms to ISO 19115 standards. The GeoNetwork metadata portal is directly accessible from Geo-Wiki or directly at: <http://geowiki.felis.uni-freiburg.de:8080/geonetwork/srv/en/main.home>

2.1. Map layers and data products

Geo-Wiki displays three global land cover products on top of Google Earth: GLC-2000, MODIS v.5 and GlobCover. The GLC-2000 was developed by the Joint Research Centre (JRC) of the European Commission for the reference year 2000. Developed using SPOT 4 satellite imagery at a resolution of 1km, more than 30 teams contributed to a series of regional windows in a bottom-up approach (Bartholomé and Belward, 2005). A single product with 22 global land cover classes was created from the regional windows using the Land Cover Classification System (LCCS) as a common framework (Di Gregorio and Jansen, 2000). The MODIS land cover product (MOD12Q1 V005) was created by Boston University using the Moderate Resolution Imaging Spectroradiometer instrument on the NASA Terra Platform using data from the year 2005 at a resolution of 500 m (Friedl et al., 2010). The MODIS land cover data set uses all 17 classes of the International Global Biosphere Project (IGBP) legend (Loveland and Belward, 1997) and was created using a global classification approach. Version 5 (MOD12Q1 V005) is the most recent product available. GlobCover is an ESA initiative carried out at the JRC to produce a global land cover map for the year 2005–2006 using data acquired from the MERIS sensor on-board the ENVISAT satellite (Bicheron et al., 2008). GlobCover 2005 is intended to update and complement existing comparable global products such as the GLC-2000 and provide a finer spatial resolution (300 m). Globcover 2009 was released in December 2010 (Bontemps et al., 2011).

Maps for the visualization of spatial disagreement were created for each pair of land cover products and are displayed using a WMS. These maps are used to highlight areas where the disagreement is the largest and where additional validation is required in the cropland and forest domains. To create these disagreement maps, the individual land cover products were first aggregated to a common grid with a resolution of $0.125^\circ \times 0.125^\circ$. This equates to an aggregation of 14 pixels for GLC-2000, 30 pixels for MODIS v.5 and 45 pixels for GlobCover. The average cropland and average forest cover for each aggregated pixel were then calculated. The disagreement was determined by examining the amount of definitional overlap between legend categories as described in Fritz et al. (2011b) and expressed in the form of lookup tables. The lookup tables were then applied to each pair of land cover products to create maps of disagreement in the forest, cropland and combined domains. An example is shown in Fig. 1a, which highlights a large area of disagreement in the USA in the cropland domain between MODIS and GlobCover. Fig. 1b and c provides the land cover from MODIS showing large areas of cropland and GlobCover, which indicates various classes of shrubland. Fig. 1d is a high resolution Google Earth image in an area of high disagreement that clearly shows a patchwork of agricultural fields. Thus it is clear that the MODIS product better represents the situation than GlobCover. It is these large areas of disagreement that Geo-Wiki is targeting in its crowdsourcing efforts. These disagreement maps

will be registered in the Global Earth Observation System of Systems (GEOSS) portal in the future and will be available for display by any WMS or WCS.

Data contributions are stored in a Postgresql database. This includes information about the user, the location of the pixels in the three global land cover maps, the land cover types according to the legends of the maps, and the land cover information from the user. A subset of these contributions was used to validate a hybrid cropland map in Africa (Fritz et al., 2011c), which can be viewed and downloaded from agriculture.geo-wiki.org.

2.2. General framework and system components

Fig. 2 provides a schematic of the general Geo-Wiki architecture, which consists of different standard components integrated into a single portal. The map layers and data products described in section 2.1 are contained in two separate repositories shown at the bottom of Fig. 2. The first repository contains the global land cover, disagreement and hybrid maps. These datasets are displayed using a WMS that uses the open source MapServer data rendering engine (mapserver.org). This software was originally developed by the University of Minnesota and is now a project within the Open Source Geospatial Foundation (OSGeo). The second repository contains a database of the Geo-Wiki users, their land cover contributions, and the pixel polygons with attribute data from the three global land cover maps. This database is accessed by the web portal to authenticate users, access the pixel polygons and store the contributions from the users. More information about the database is provided in section 2.3.

The web portal operates using PHP running on an Apache web server (version 2.2.16) together with the WMS. The server runs Gentoo Linux, and a very fast internet backbone underpins the system. The client browser loads the website geo-wiki.org, which is written in PHP and JavaScript, and uses the Google Earth API (Application Programming Interface), which is the only component that is not open source in Geo-Wiki. To view the land cover, disagreement or hybrid maps in Geo-Wiki, the client computer initiates a 'GetMap' request in Javascript to the Geo-Wiki WMS and then uses the 'CreateGroundOverlay' routine from the Google Earth API to overlay any of these layers onto Google Earth.

The reasons for choosing Google Earth were the 3D visualization capabilities and access to high resolution imagery via the Google Earth API, which were not available at the time in 2D Google Maps. The advantage is that a stand-alone 3D-application does not require installation on the client computer but a simple web browser can be used to access the application. However, the appropriate plug-in for Google Earth must be installed, which is a potential barrier to those individuals who simply want to view the application quickly. Other advantages of the 3D visualization include the ability to use the height perception to differentiate between land cover types, e.g. shrubs and trees, and the fact that the presence of high resolution imagery can be seen immediately on Google Earth. In Google Maps, the user must zoom in before the high resolution images appear. However, now that high resolution imagery is available in Google Maps, a 2D application may be developed in the future using Openlayers.

2.3. Database design

The database behind Geo-Wiki is the open source PostgreSQL relational database with a PostGIS extension to allow for spatial queries. The database stores the user details, user validations and the pixel polygons of the three global land cover data sets. Although the global land cover maps can be viewed as a semi-transparent layer on Google Earth, the bounding coordinates of each pixel are

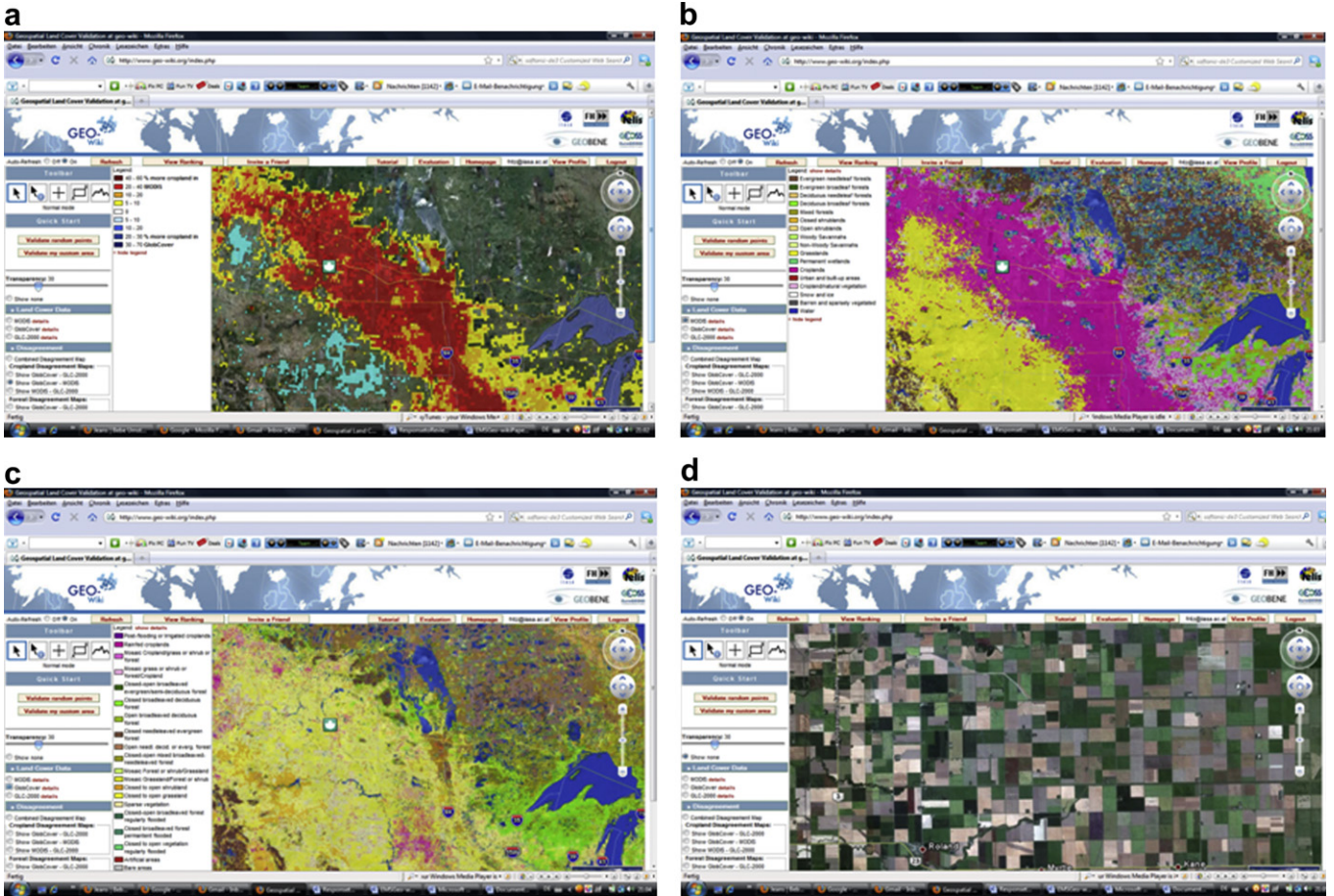


Fig. 1. An example showing the disagreement between a pair of land cover maps in the cropland domain: a) Disagreement map between MODIS and GlobCover; b) MODIS land cover; c) Globcover for the same area; d) drilling into a pixel of disagreement which shows cropland on Google Earth.

stored in the database. This representation was chosen in order to quickly retrieve the outlines of the pixels and their attributes at any given point on the Earth’s land surface. This is illustrated in more detail in section 3.1. The pixel polygons are stored as binary PostGIS geometry types with a spatial reference system (SRID) of 4326

(WGS84/latlon). The PostGIS language extension allows for the very easy and efficient export of data into different formats by supporting queries such as ‘select AsGML (the_geom) from tbl_polygon where id = 1000’. To retrieve a specific polygon from a spatial query requires a database index on the geometry. The commonly accepted

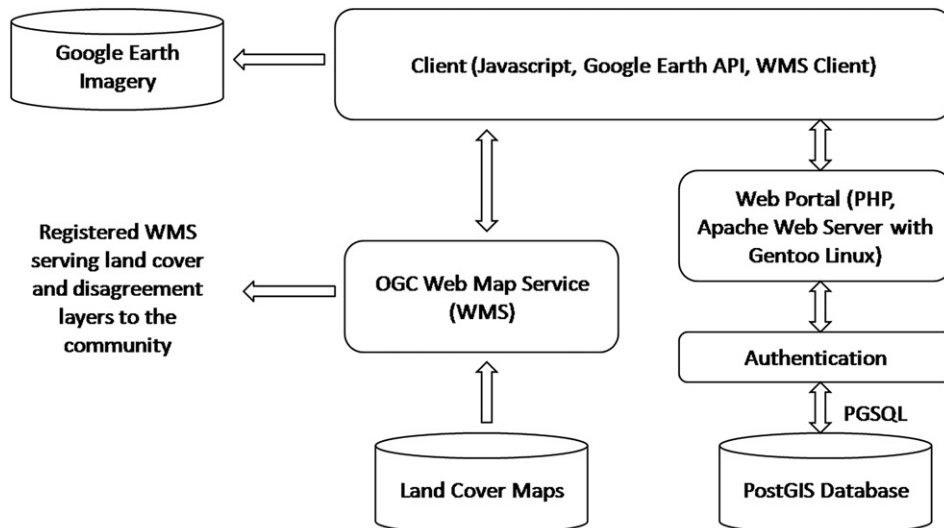


Fig. 2. Architecture of the Geo-wiki system.

GiST index has been used for this purpose and has proven to be very fast, even on a table holding nearly two billion polygons. The user contributions are stored in a separate table either as POINT or POLYGON geometry depending on whether the contributor has provided information on a single pixel or a whole area. For a single pixel, the POINT holds the coordinates of where the user clicked on Google Earth rather than the land cover pixels as this is a much more efficient way to store the data. When required, the point data can be matched to the pixels of the three land cover data sets using a simple query function. The id of the user is also stored so a ranking table can be created to display the top contributors, and to allow users to download their own contributions for their specific purposes.

2.4. Modularization of Geo-Wiki

Geo-Wiki began as a generic tool for attempting to crowdsource land cover but its potential in serving other areas has led to the development of different land cover type specific modules. For example, a variant of Geo-Wiki for agriculture was developed (agriculture.geo-wiki.org) where users focus on using Google Earth to determine what percentage of cropland exists at a given location within a pixel. A competition was run for young scientists at IASA to provide data for as many locations as possible. This information was used to assess the accuracy of the hybrid cropland map for Africa discussed earlier. The results showed an improvement in overall accuracy when compared to individual land cover products (Fritz et al., 2011c). Variants for biomass (biomass.geo-wiki.org), urban areas (urban.geo-wiki.org) (Fritz et al., 2011a) and human impact (humanimpact.geo-wiki.org) are also available. This modularization is possible because the Apache server supports virtual hosts. Each instance of Geo-Wiki has the same IP address but

the server provides redirection to the correct variant. When agriculture.geo-wiki.org was developed, different functionality was added that varied from the core Geo-Wiki application. These variants have now been reconciled into a single version with the same functionality, using environment variables to determine which client variant is requested by the user.

3. Overview of Geo-Wiki

The Geo-Wiki application can be found at www.geo-wiki.org where the home page (Fig. 3) provides some general information about Geo-Wiki. Guest access is available or users can register for an account. The advantage of registration is that the data contributions are stored by user id and the five registered users who have contributed the most land cover data are listed on the home page in rank order. Once inside the application, it is also possible to view the complete ranking by user. Google Translate is implemented in all languages although more specific language support will be provided in the future.

Once in the system, Google Earth is displayed with functionality to rotate the Earth and to zoom into any land surface to begin land cover assessment. The user can also plot any of the global land cover maps (GLC-2000, MODIS, GlobCover) on top of Google Earth as shown in Fig. 4, or the user can display the disagreement maps between any pair of land cover products (Fig. 5). As discussed in section 2.1, these disagreement maps highlight areas where further validation is needed.

3.1. Assessing land cover

There are different ways in which the user can assess land cover. The simplest way is to click on the button labeled *Validate random*

The screenshot shows the Geo-Wiki home page. The browser window title is "Welcome to Geo-Wiki Project - Mozilla Firefox". The address bar shows "geo-wiki.org/login.php?ReturnUrl=/index.php". The page content includes:

- Header:** "HELP TO VALIDATE GLOBAL LAND COVER" with logos for IASA, FH, Felis, GEOBENE, and GEOSS.
- Left Navigation:**
 - » Home
 - » Instructions
 - » Geo-Wiki branches
 - » Publications
 - » Download Data
 - » Media
 - » Supporting projects
 - » Related projects
 - » Data sources
 - » Upcoming Events
 - » Contact us
 - » Disclaimer
- Main Content:**

The Geo-Wiki Project [Tweet 0]

The **Geo-Wiki Project** is a global network of volunteers who wish to help improve the quality of global land cover maps. Since large differences occur between existing global land cover maps, current ecosystem and land-use science lacks crucial accurate data (e.g. to determine the potential of additional agricultural land available to grow crops in Africa). **Volunteers** are asked to review hotspot maps of global land cover disagreement and determine, based on what they actually see in Google Earth and their local knowledge, if the land cover maps are correct or incorrect. Their input is recorded in a database, along with uploaded photos, to be used in the future for the **creation of a new and improved global land cover map.**

View publication Watch the tutorial video online Download Data

[Satellite map showing land cover data]
- Right Side:**
 - Try Geo-Wiki** [Try as guest]
 - Login**

Login existing user

Email:

Password:

Remember me

[Forgot password?](#) [Register here!](#)
 - Geo-Wiki top 5 validators**

1	Rubul Hazanka	12714
2	Simone Ortner	8324
3	Ahmed Rabia	6121
4	JP Ardila	5905
5	Carlos Di Bella	4596

[View complete ranking](#)
 - Google Translate**

Select Language

Fig. 3. The Geo-Wiki home page.

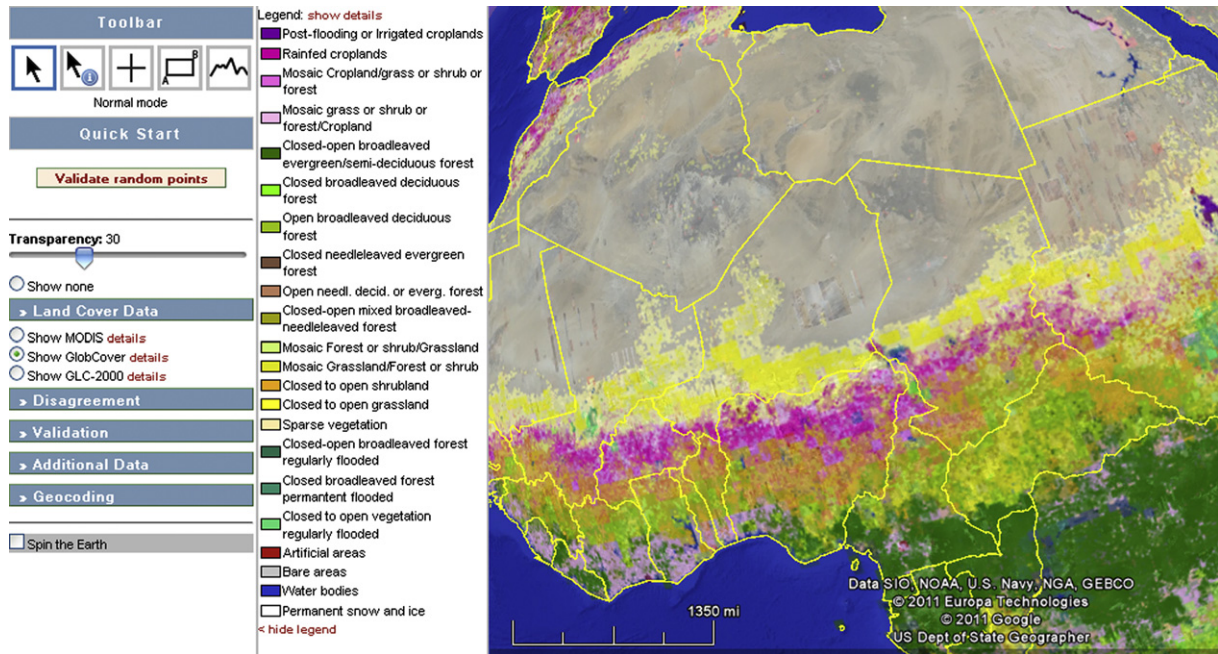


Fig. 4. Plotting the GlobCover land cover product on Google Earth.

points. This will automatically zoom the user into a degree confluence point (i.e. a latitude/longitude intersection) and show the outlines of the pixels of the three land cover datasets (i.e. MODIS, GlobCover and GLC-2000), indicating on the right what the land cover types are in the pixels that contain the confluence point as shown in Fig. 6. Based on what the user sees on Google Earth, they should indicate whether the legend description for each land cover product is a good or bad match or whether they are not sure due to insufficient visual information. A sliding bar to indicate confidence in the assessment of land cover in the land cover products is also provided. The *Submit* button will write this

information to a database. The user can then continue to further assess the land cover at random points.

Users can also undertake the land cover assessment process by automatically having Geo-Wiki zoom into the location under which they are registered, e.g. workplace, home, etc. Land cover can then be assessed in an area with which the user is familiar, where points will be selected randomly across a 100 km grid around the user's location. Alternatively, the user can zoom into any location on the Earth's surface and undertake land cover assessment. The buttons in the toolbar shown in Fig. 7 (located in the upper left hand corner of the screen) allow the user to choose a location on the Earth's

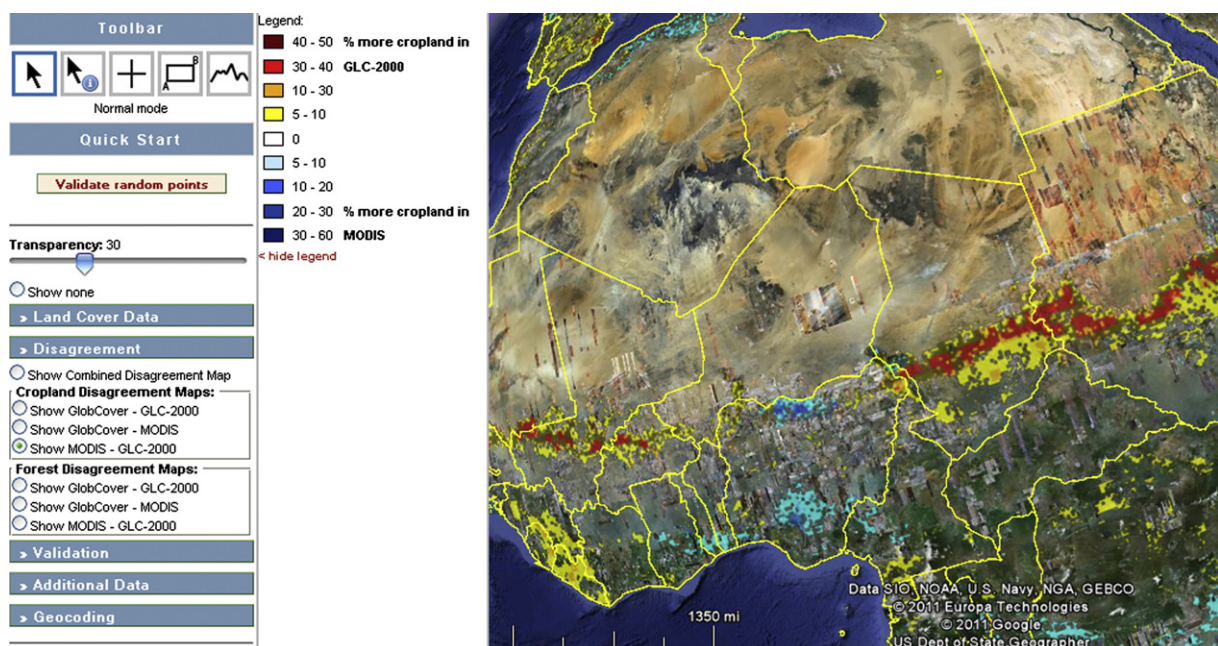


Fig. 5. Plotting a cropland disagreement map between the GLC-2000 and MODIS land cover products.

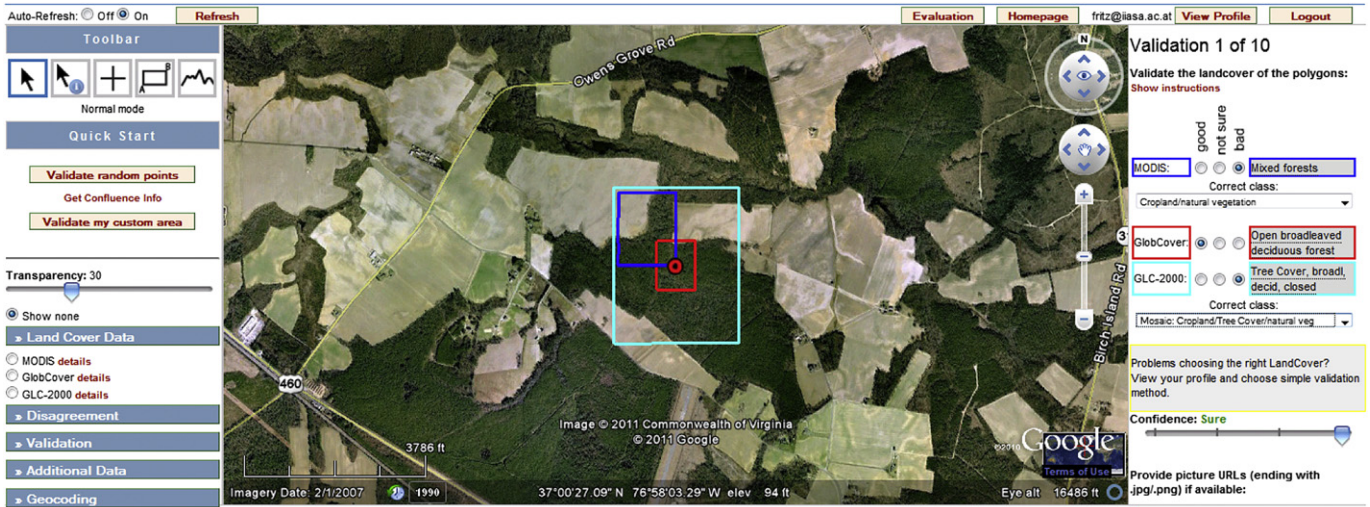


Fig. 6. Assessing land cover at a random location on the Earth’s surface for MODIS, GlobCover and GLC-2000 using Google Earth with proposed corrections to the land cover information and a confidence scale bar.

surface but requires the user to be zoomed in sufficiently before the outlines of the land cover pixels will appear. The first button in the toolbar with an arrow indicates normal mode. Double clicking anywhere on the Earth will zoom the user in further. The next three buttons in the toolbar are used to choose a point. The second button from the left is the information button. Clicking anywhere while this button is enabled will highlight in red the points at which the land cover will be assessed. Double clicking on one of these red points will zoom the user into that point and show the pixels for

land cover assessment. The third button, which contains a cross-hair, does the same thing but does not require clicking on a red point. The fourth button allows the user to drag the cursor across an area and highlight a point within that area for land cover assessment. The disagreement maps, like that shown in Fig. 5, can also be used to help focus on areas where more validation is needed. Finally, users can define a systematic grid of points for assessing land cover and adjust the granularity of the grid as shown in Fig. 7. This feature is accessed by clicking on the View Profile button

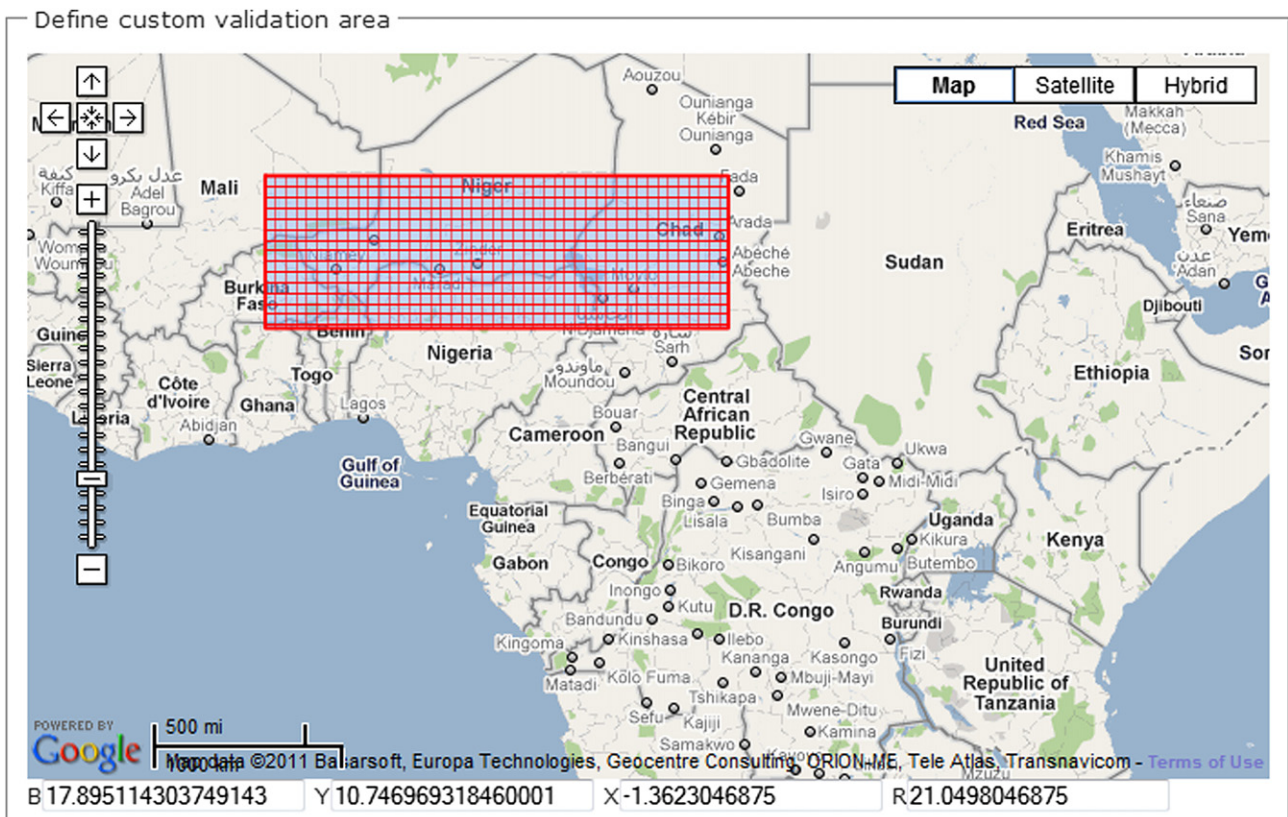


Fig. 7. Example of a 0.5 degree systematic validation grid over western Africa in areas of high uncertainty in cropland extent.

followed by the Custom Area link. This feature will be extended in the future to add the possibility of random data collection within the chosen area or those locations with the highest disagreement.

The assessment of land cover in relation to the land cover products is not always straightforward. This is partly because of the types of images that are available on Google Earth. A base layer of satellite imagery covers the entire land surface at a resolution of 15 m. Supplied by [Terrametrics \(2010\)](#), 30 m Landsat multi-spectral bands have been pan-sharpened using the 15 m resolution panchromatic band via a data fusion technique. Then where available, higher resolution satellite imagery such as Quickbird or GeoEye and aerial photographs are incorporated, which are updated and expanded to other areas on a continual basis ([Google, 2010](#)). Since it is not possible for Geo-Wiki to determine the resolution of the images on the fly, the user is asked to indicate whether high resolution imagery was used in determining the land cover type (as shown at the bottom right of [Fig. 6](#)). A *Show help* link underneath this option provides the user with an example of a Landsat image compared to a high resolution GeoEye image to aid in making this determination. At present, approximately 30% of the Earth's land surface (or 50% of the world's population) is covered by high resolution imagery ([Google, 2011](#)), e.g. most of Europe, but some of the more rural locations are still only covered by the lower resolution Landsat base imagery, where determination of land cover is more difficult. To aid in helping users assess the land cover, there are online instructions and a video on YouTube accessible from the home page, and a step-by-step tutorial once inside the system. All of these resources provide basic training on recognizing different land cover types and different image resolutions on Google Earth. A test is given at the end of the step-by-step tutorial, which allows users to be classified by the level of skill in identifying land cover

from Google Earth and provides a form of quality assurance information for the contributed data. This feature has only recently been added so will continue to be expanded over time.

[Fig. 8](#) shows a layer that can be added, which is coded in red, yellow and green to indicate areas where there are no, few or some data contributions, respectively. Under the Validation menu on the left-hand side, there is a button labeled Load Geo-Wiki members, which shows where the different registered users are located around the world.

3.2. The use of original and simpler legends

The legends associated with each global land cover map differ both in terms of the number of classes and the definitions of classes even though they may appear to be semantically similar. The default setting in Geo-Wiki is to use the original legends of each land cover product referred to as the complex setting. It is possible to view the full definition of each land cover type associated with the three land cover products by a) displaying one of the products on Geo-Wiki and then b) clicking on the 'show details' link in the legend (as shown in [Fig. 9](#)).

It is also possible to choose the simplified legend of [Herold et al. \(2008\)](#) onto which all global land cover datasets can be mapped. This simplified legend consists of 13 classes and can be accessed by pressing the *View profile* button followed by the *Validation method* and changing this to *simple*. It is envisaged that a greater number of users will contribute land cover data because it will be easier using this legend. Moreover, a simplified legend is needed to create a single hybrid land cover product. However, we also recognize that users have their own land cover classes specific to their needs, which is discussed further in section 4.2.

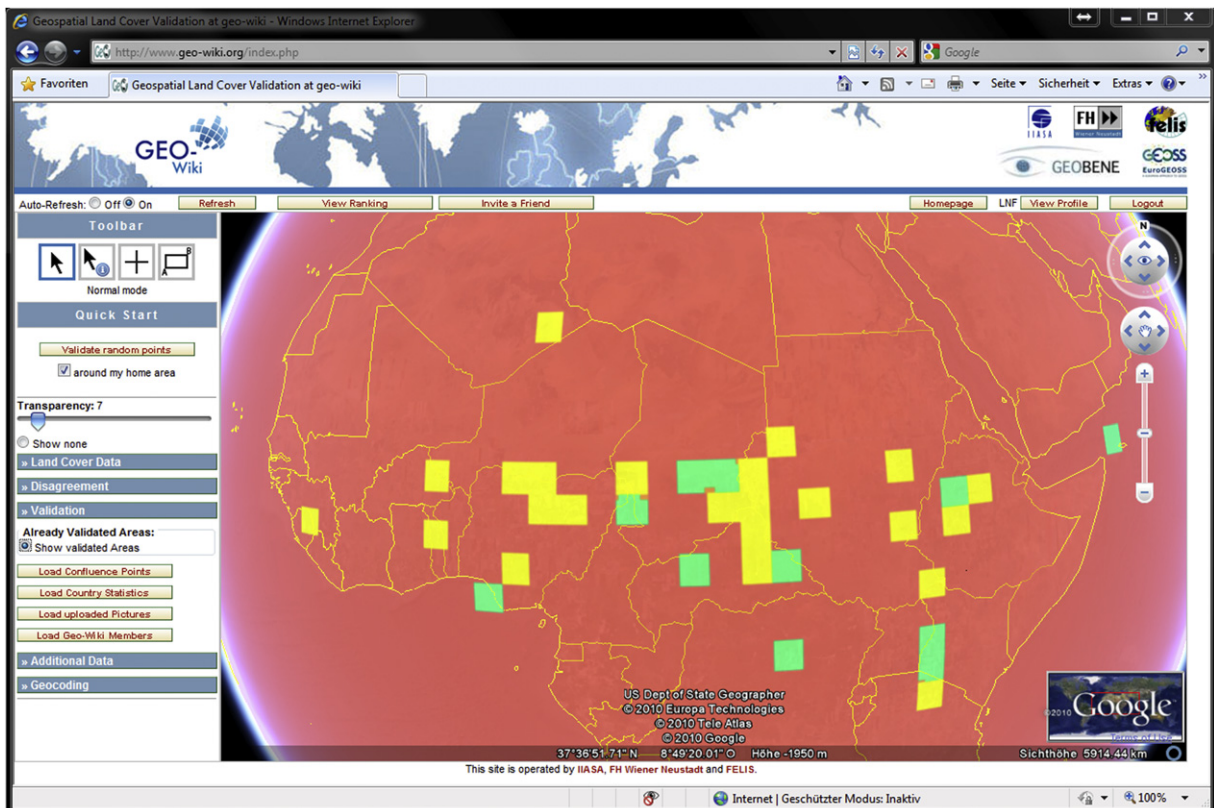


Fig. 8. Red, yellow and green areas indicate how much crowd-sourced information has been contributed (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

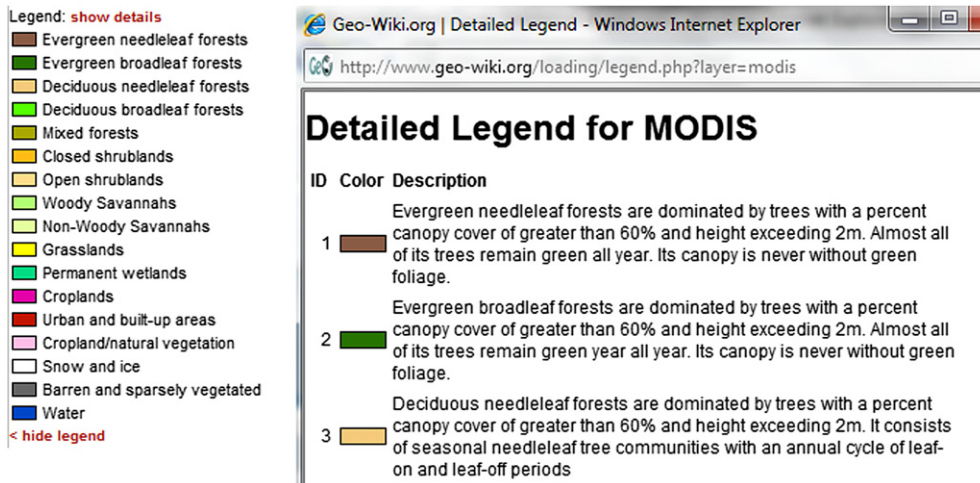


Fig. 9. Clicking on the 'show details' link in the MODIS land cover legend will display the full legend definitions associated with this product. Comprehensive legend definitions are also available for GlobCover and GLC-2000, which are accessed in the same way.

3.3. View confluence points, country statistics, geo-tagged photos and FRA 2010 land blocks

Under the Validation menu, there are several options to load additional data in Geo-Wiki such as confluence points. Clicking on one of these points will provide a link to information stored on the Degree Confluence Project website (<http://confluence.org/>), which includes the pictures and stories uploaded by people who have visited these points. Fig. 10 shows the type of information that would be displayed at the location corresponding to Fig. 6.

A second option under the Validation menu is to load national statistics. Clicking the icon that will appear in each country will launch a window containing bar charts of forest and cropland statistics for 2000 and 2005 from FAOSTAT (FAO, 2005) along with how these compare to the minimum and maximum estimates from the GLC-2000, GlobCover and MODIS. These estimates were derived through the legend definitions, e.g. forest classes in GlobCover vary between a minimum of 20% and a maximum of 100% coverage. An additional estimate for the forest domain is also provided by the Vegetation Continuous Field (VCF) product for characterizing forest cover at thresholds of 15% and 60%. The VCF

has been derived from all seven bands of the MODIS sensor on NASA's Terra satellite (Hansen et al., 2003, 2006). The source of this data set is the Global Land Cover Facility (<http://www.landcover.org>). This product contains proportional estimates of vegetation cover including woody vegetation, herbaceous vegetation and bare ground. Clicking on an individual bar chart will allow the user to see a larger version of the graph with a detailed explanation of each item in the graph. Fig. 11 shows an example of forest cover statistics for Uganda.

Geo-tagged photos that have been uploaded to the site can also be viewed by selecting the *Load Uploaded Pictures* option under the Validation tab or as separate archives listed under the Additional Data link. These pictures come from a variety of sources such as the Global Monitoring for Food Security Project in Malawi (Fig. 12) and photo archives such as Panoramio (<http://www.panoramio.com/>) and the University of Oklahoma (<http://eomf-dev.ou.edu/photos/>). These photos can lead to potential improvements in the quality of land cover by providing additional ground-based information to supplement the satellite images on Google Earth, especially in locations where high resolution imagery is not available or in areas where large changes in land cover have occurred. Geo-Wiki also

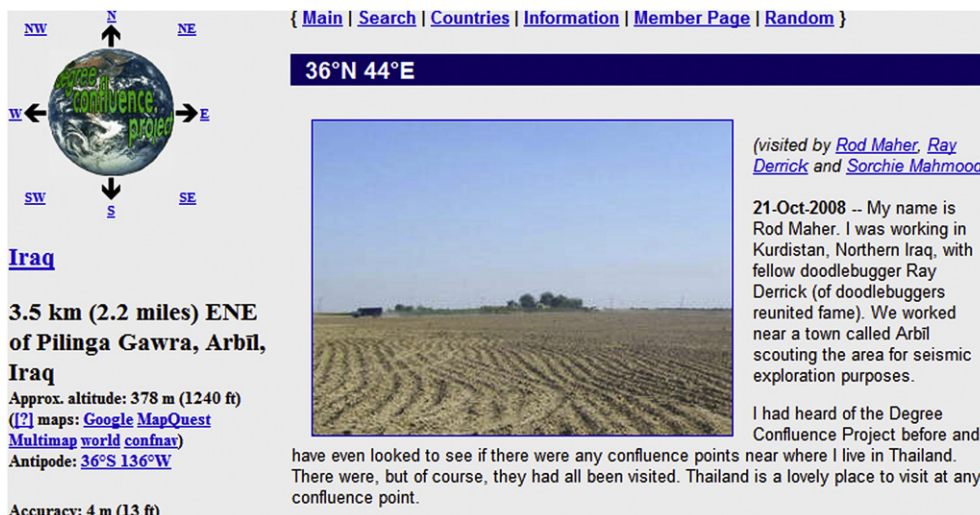
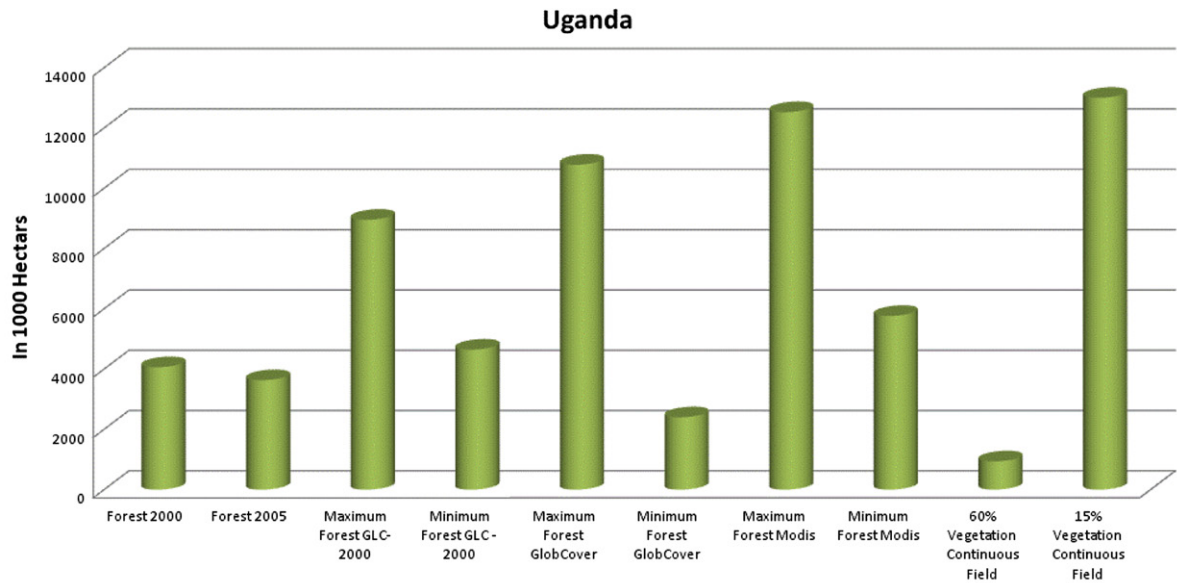


Fig. 10. An example of a link to the confluence point project to aid in assessing the land cover shown in Fig. 6.



Forest Statistics

The Figure reports forest area per country using different data sources, FAO statistics and forest cover data derived from different global land cover maps (GLC-2000, Globcover and Modis).

Column	Statistics and data sources
Forest 2000	FAO reported statistics for the year 2000
Forest 2005	FAO reported statistics for the year 2005

Fig. 11. Forest cover statistics from FAO (2005), the land cover products and the VCF for Uganda.

allows users to upload their own geo-tagged photos and encourages the crowd-sourcing of this social media. A Geo-Wiki cross-platform smart phone application is currently being developed to allow users to annotate their photos with land cover and other information and upload these directly to Geo-Wiki. In addition to providing an attractive way for users to visualize their photos online, the potential of geo-tagged photos for the training and

development of land cover datasets has been demonstrated by Leung and Newsam (2010), which could be easily extended to land use classification.

Finally, it is possible to load the outlines of the 10 and 20 km land blocks of the Forest Resource Assessment (FRA) 2010, which shows users where this assessment is currently taking place. Discussions with FAO within the FP7 funded project EUROGEOS

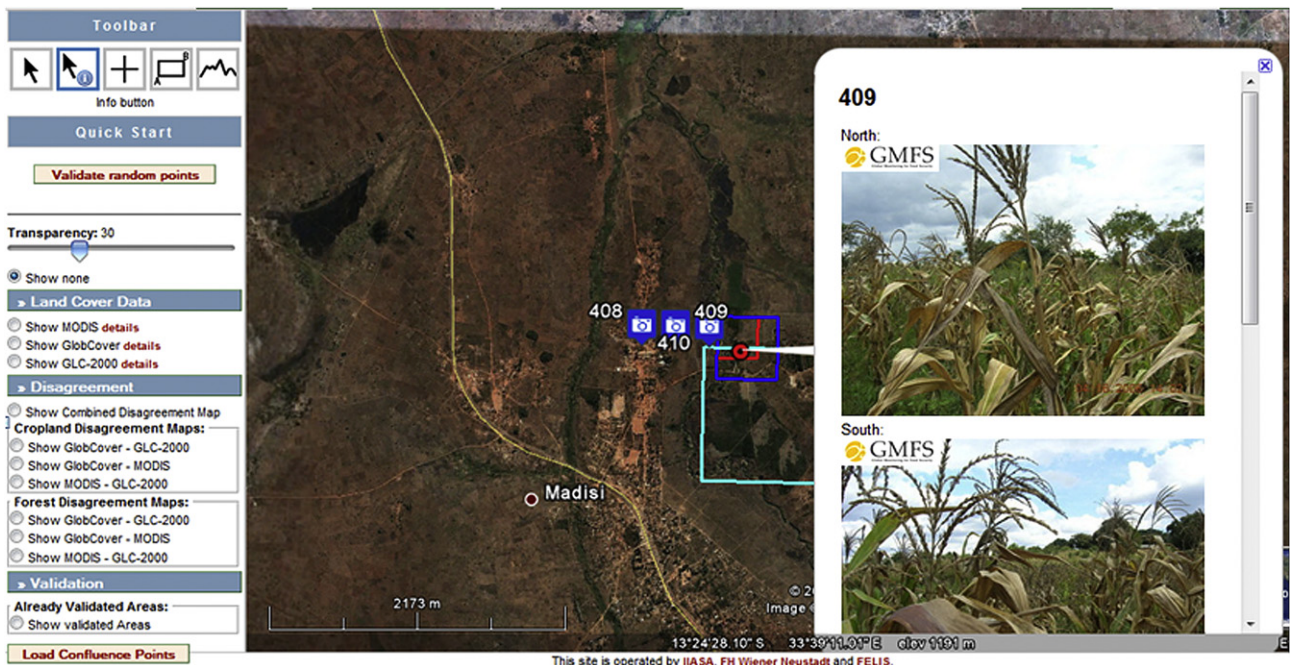


Fig. 12. Example of geo-tagged photos from the GMFS project taken in four orientations.

are ongoing to display the interpretation of forest change from FRA2010 along with the original Landsat images within these land blocks (see section 4 for more information).

3.4. View NDVI profiles for each pixel

A recently added feature is a display of the five year average NDVI (Normalized Different Vegetation Index) profile (2003–2007) at 10 day intervals across the year. The archive of SPOT-VEGETATION data has been provided by the MARS (Monitoring Agricultural Resources) unit of the JRC, which has been processed by VITO-BE to create NDVI under the framework of the existing MARSOP contract. NDVI is useful for differentiating between evergreen and deciduous forest or vegetated versus non-vegetated areas. Fig. 13 shows an example of two different NDVI profiles and the corresponding images on Google Earth for an evergreen, needleleaved forest on the left and a deciduous forest on the right in Germany. The NDVI profile on the right shows a more pronounced dip in the NDVI during the winter months when the deciduous forest loses its leaves. These NDVI profiles can be used to aid in differentiating between different types of forested area.

3.5. Viewing the hybrid cropland map

The hybrid cropland map developed by Fritz et al. (2011c) can be accessed through the agriculture variant of Geo-Wiki (<http://agriculture.geo-wiki.org>). It is referred to as the IIASA/IFPRI calibrated map and shows percentage cropland for Africa. Other cropland maps can also be displayed in Geo-Wiki including the crop and pastureland maps of Ramankutty et al. (2008) and the global cropland extent maps of Pittman et al. (2010).

4. Experiences with Geo-Wiki to date

4.1. Data collection through Geo-Wiki

Google Analytics was added to Geo-Wiki in June 2010 to monitor the incoming traffic to the site. Since then, the site has been visited just under 20,000 times from 144 countries around the world with an average time spent on the site of around 5 min. The Geo-Wiki user database indicates that more than 600 people have now registered as Geo-Wiki contributors. Together these users have provided more than 66,000 contributions to Geo-Wiki, which have been entered into the database from the main Geo-Wiki website or the different

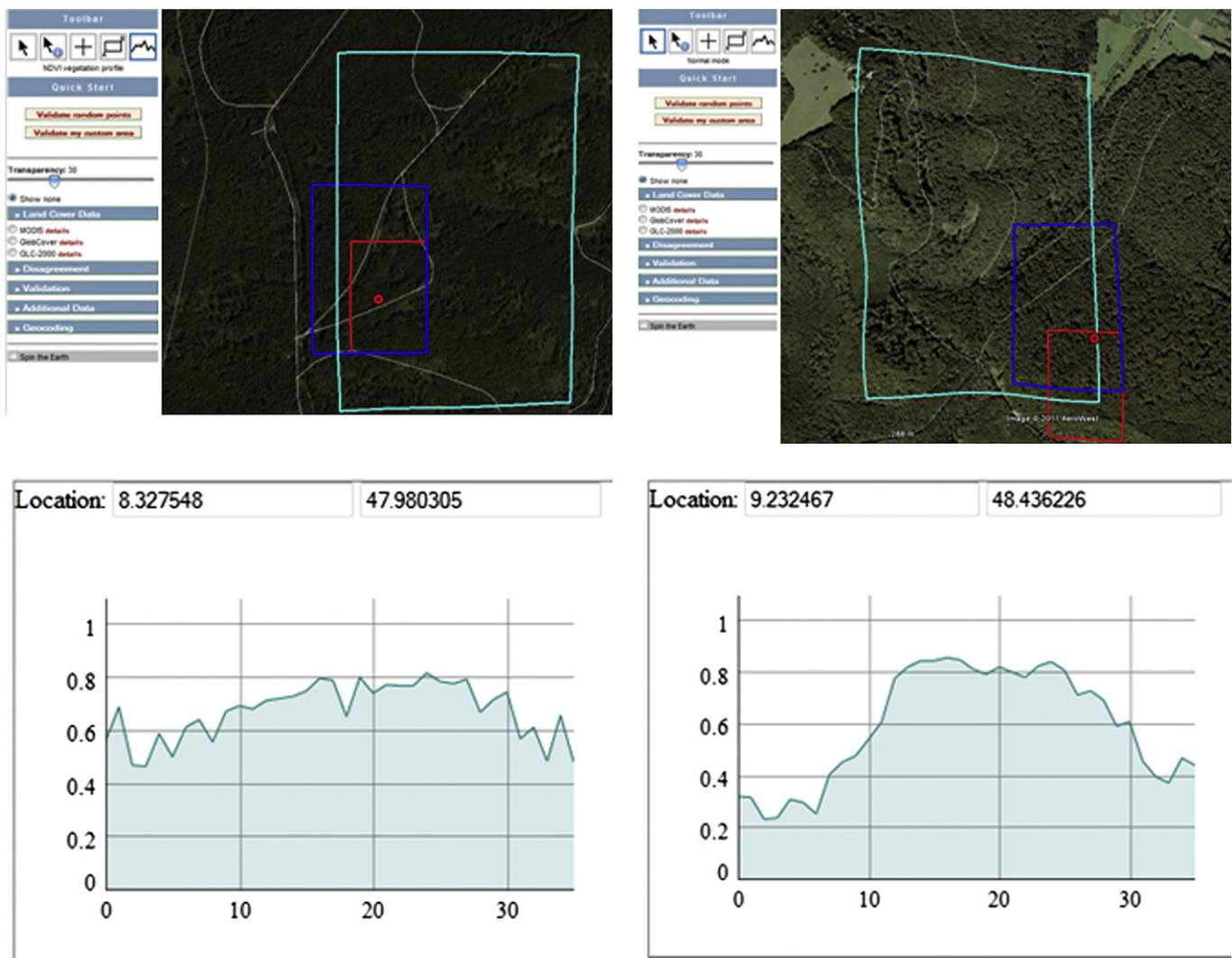


Fig. 13. Google Earth images and NDVI profiles for evergreen, needleleaved portion of the Black Forest (left) and deciduous forest in an area east of the Black Forest (right) which shows the NDVI values are low from Dec to March.

variants such as [agriculture.geo-wiki](http://agriculture.geo-wiki.org) and humanimpact.geo-wiki.org. The most recent online tutorial, which is posted in YouTube, has had 132 views, which replaces the previous tutorial that had over 450 views.

Of the 66,000 points contributed to date, the majority has been provided by a relatively small number of people from three main sources. The first set comprises remote sensing experts or scientists with a geospatial background who were recruited through a competition run at the IGARSS (International Geoscience and Remote Sensing Society) conference in 2010. The second group was young scientists recruited in a competition to specifically validate agricultural areas in Africa at latitude–longitude intersections across Africa for use in validation of the African hybrid cropland map (Fritz et al., 2011c). The prize in both competitions was a digital camera. The third source, which has generated the majority of contributions to date, comes from a recent competition on humanimpact.geo-wiki.org in which the prize was Amazon vouchers and co-authorship on a paper. In this competition, a facebook group was formed and social interaction with users was part of the process. The competition was widely advertised through mailing lists and academic contacts so the profile of the main contributors was more varied; however, many have either a background in GIS or remote sensing, or have post-graduate education in another field.

The statistics are reported on the front page of Geo-Wiki in a ranking table, which shows the number of contributions by individual. This will be modified in the future to display the branch to which the contributions have been made and indicate the period of contribution. Other features will be added that allows users to query these statistics, e.g. plotting the contributions over time.

4.2. Lessons learned and future improvements

It is clear from the three data collection campaigns that turning Geo-Wiki into a sustainable mechanism for land cover assessment will necessitate modifications to the system and require the development of an online community, whether comprised of remote sensing experts with an interest in land cover or the broader public, who would need engagement on a broader environmental level. At present the system only promotes one-way communication, i.e. users provide assessments of the land cover although they can download these and then use them for their own purposes. However, the users do not receive any feedback, e.g. the effect of providing the information in terms of potential improvements to land cover, or any social interaction with other users or the scientists on the Geo-wiki team (although some interaction through facebook occurred in the last campaign). The conversion of Geo-wiki to a two-way communication platform with embedded social networking tools is one of the main improvements that must be implemented if communities of experts and citizens are to be built and sustained on a more long-term basis. This message is echoed by Newman et al. (2010), who reviewed principles of good citizen science and have provided guidelines for successful web mapping applications. As part of developing the community, the Geo-Wiki team of scientists must be active within this community, raising awareness of land cover issues; initiating campaigns; providing updates on the effects of collective user contributions; and generally guiding the crowd in a type of collaborative learning process (Voinov and Bousquet, 2010). Through a collaborative land cover mapping effort, groups could work together or individuals that provide land cover assessments of the same area could discuss their findings, particularly in those areas that were difficult to identify because of low resolution imagery or heterogenous landscapes. The injection of expertise from scientists and from individuals with knowledge of a particular area could provide a very stimulating learning exercise. A feature will be added that allows

users to display their past contributions, which can then be corrected, especially in situations where they have improved their ability to identify land cover and want this to be reflected in their contributions. These types of elements are crucial if ordinary citizens are to be engaged.

Newman et al. (2010) also highlight the need to add fun elements to the system. An Austrian funded project called LandSpotting (<http://www.landspotting.org>), which began at the start of 2011, addresses the creation and implementation of a set of games that will collect land cover information as part of game play. A prototype facebook game is currently available and will be launched at the end of 2011. Other games are currently in development for tablets and smart phones. This is a totally different approach to community building but has the potential to reach a different audience to that of the scientific and environmentally engaged individual.

Experimentation with data quality is currently ongoing through a competition to help assess the quality of a biofuel land availability map (humanimpact.geo-wiki.org). Contributors were given the same 100 points to assess at the beginning and the end of the competition, which will be used to gain an understanding of quality and consistency, and will be reported in a future paper. Some interaction with participants was achieved through a facebook group, where participants asked questions about some hard to classify areas. The improvements which participants made during the competition are still to be analyzed but the initial results indicate that not all validations provided by the users are of the same quality. Different mechanisms will be implemented to guarantee a certain degree of quality. These include: 1) systematic checking of contributions by experts; 2) implementation of an internal rating system that will indicate the degree to which the contributions can be trusted; 3) a system whereby multiple contributors are given the same areas to assess, which can then be discussed in a forum. The latter mechanism will ensure a continual process of learning and improve user confidence in land cover assessment. The test at the end of the tutorial can also be used to provide a test of initial skill in assessing land cover. This can be combined with information about their previous experience (filled in as part of the registration process), user ratings and a score based on how well they assessed sites for which the land cover type is already known. Bishr and Mantelas (2008) suggest a composite method of rating users based on their experience and knowledge, their proximity to the information being provided, ratings from other users and the frequency of contributions provided at the same point, which could be adapted for this purpose. Scores will also change over time as more experience is gained.

We will also test Linus' law, i.e. does the quality increase as the number of contributions at the same place increases (Haklay et al., 2010). A methodology will be developed that uses information from these frequency distributions to integrate crowdsourced information in the development of a hybrid land cover map.

Feedback from users has indicated that Geo-Wiki would be very useful if users could define their own legend classes in their own language. This user-defined legend could be used to assess the current global land cover products based on these legends or more usefully, to assess maps supplied by the user through a WMS or WCS. This would diversify Geo-Wiki from a purely crowdsourcing application to a provider of services and is scheduled for addition in the next year.

Further developments are planned with respect to a deforestation Geo-Wiki in collaboration with FAO's FRA2010 where the land blocks are now currently displayed on Geo-Wiki (see section 3.3). Once these blocks are populated with the interpretations of deforestation and land change from FAO and JRC, users could examine these changes based on the original Landsat imagery and very high resolution images for dates that match those of the

FRA2010. The same concept could be used for monitoring REDD+ (Reducing Emissions from Deforestation and Forest Degradation) projects, which take place in areas threatened by deforestation. By showing these areas on Google Earth and adding additional timely high resolution images (e.g. GeoEye or WorldView), crowdsourcing could be used for transparent and open monitoring of the success of REDD+ projects in the future.

5. Conclusions

This paper has introduced an online platform for the crowdsourcing of land cover using Google Earth including the architectural design and the evolving, modular structure. However, it should be stressed that the proposed tool does not intend to replace current land cover validation activities by experts, but can potentially complement some of those activities by providing either additional data (subject to quality assurance) or the tools to undertake validation. For example, scientists can use Geo-Wiki to design and collect their own validation samples; the JRC has already used Geo-Wiki for this purpose in validating their cropland map.

Through the collection of data on land cover and geo-tagged photos, Geo-Wiki provides the means to answer many different research questions such as: How can different types of data be integrated to create a hybrid land cover product? What innovative methods can we develop for including the skill of the users in creating a hybrid product? What is the quality of the data contributions to Geo-Wiki? How can this wealth of soft validation data (including geo-tagged pictures) be used in training and testing of land cover classification algorithms? How do we create a sustainable community that engages ordinary citizens? Each of these questions is being actively pursued as part of an ongoing research agenda. The final question is particularly relevant as it is clear that the majority of contributions to date have been provided by remote sensing experts or scientists recruited through competitions and not ordinary citizens or the 'crowd'. Thus Geo-Wiki is currently more of an expert-sourcing system than a crowdsourcing one. To reach out to a wider audience and build a sustainable community around Geo-Wiki will require a step change in the application, i.e. addition of social networking tools and feedback mechanisms that motivate individuals to participate. The gaming aspect will also be interesting to monitor as it has the potential to massively increase the amount of data collected in a very different way to community building that is built around a common goal of improving land cover. The ongoing experiments with data quality will address whether citizens can classify land cover and what improvements are needed to ensure that the process becomes more scientifically rigorous and replicable. At a minimum, they will lead to a robust mechanism for filtering out the lower quality contributions from those of high, acceptable quality.

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References

- Bartholomé, E., Belward, A.S., 2005. GLC2000: a new approach to global land cover mapping from earth observation data. *International Journal of Remote Sensing* 26, 1959–1977.
- Bicheron, P., Defourny, P., Brockman, C., Schouten, L., Vancutsem, C., Huc, M., Bontemps, S., Leroy, M., Achard, F., Herold, M., Ranera, F., Arino, O., 2008. GLOBCOVER. http://ionia1.esrin.esa.int/docs/GLOBCOVER_Products_Description_Validation_Report_I2.1.pdf (accessed 15.12.10).
- Biradar, C.M., Thenkabail, P.S., Noojipady, P., Li, Y., Dheeravath, V., Turrall, H., Velpuri, M., Gumma, M.K., Gangalakunta, O.R.P., Cai, X.L., Xiao, X., Schull, M.A., Alankara, R.D., Gunasinghe, S., Mohideen, S., 2009. A global map of rainfed cropland areas (GMRCRA) at the end of the last millennium using remote sensing. *International Journal of Applied Earth Observation and Geoinformation* 11, 114–129.
- Bishr, M., Mantelas, L., 2008. A trust and reputation model for filtering and classification of knowledge about urban growth. *Geojournal* 72, 229–237.
- Bontemps, S., Defourny, P., Van Bogaert, E., Arino, O., Kalogirou, V., Perez, J.R., 2011. GLOBCOVER 2009: products description and validation report. URL: http://ionia1.esrin.esa.int/docs/GLOBCOVER2009_Validation_Report_2.2.pdf.
- Di Gregorio, A., Jansen, L., 2000. Land Cover Classification System: Classification Concepts and User Manual. Food and Agriculture Organization of the United Nations, Rome.
- Erl, T., 2005. Service-Oriented Architecture (SOA): Concepts, Technology and Design. Pearson Education Inc., Boston MA.
- FAO, 2005. FAOSTAT agricultural data, Food and Agriculture Organization of the United Nations. URL: <http://faostat.fao.org/faostat/collections?version=ext&hasbulk=0&subset=agriculture>.
- Flanagin, A.J., Metzger, M.J., 2008. The credibility of volunteered geographic information. *Geojournal* 72, 137–148.
- Friedl, M.A., McIver, D.K., Hodges, J.C.F., Zhang, X.Y., Muchoney, D., Strahler, A.H., Woodcock, C.E., Gopal, S., Schneider, A., Cooper, A., Baccini, A., Gao, F., Schaaf, C., 2002. Global land cover mapping from MODIS: algorithms and early results. *Remote Sensing of Environment* 83, 287–302.
- Friedl, M.A., Sulla-Menashe, D., Tan, B., Schneider, A., Ramankutty, N., Sibley, A., Huang, X., 2010. MODIS Collection 5 global land cover: Algorithm refinements and characterization of new datasets. *Remote Sensing of Environment* 114 (1), 168–182.
- Fritz, S., Bartholomé, E., Belward, A., Hartley, A., Stibig, H.J., Eva, H., Mayaux, P., Bartalev, S., Latifovic, R., Kolmert, S., Roy, P., Agrawal, S., Bingfang, W., Wenting, X., Ledwith, M., Pekel, F.J., Giri, C., Múcher, S., de Badts, E., Tateishi, R., Champeaux, J.-L., Defourny, P., 2003. Harmonisation, Mosaicing and Production of the Global Land Cover 2000 Database (Beta Version). Office for Official Publications of the European Communities, Luxembourg, ISBN 92-894-6332-5, EUR 20849 EN, 41 pp.
- Fritz, S., See, L., 2008. Quantifying uncertainty and spatial disagreement in the comparison of Global Land Cover for different applications. *Global Change Biology* 14, 1–23.
- Fritz, S., McCallum, I., Schill, C., Perger, C., Grillmayer, R., Achard, F., Kraxner, F., Obersteiner, M., 2009. Geo-Wiki.org: the use of crowd-sourcing to improve global land cover. *Remote Sensing* 1 (3), 345–354.
- Fritz, S., Fuss, S., Havlik, P., McCallum, I., Obersteiner, M., Szolgayová, J., See, L., 2010a. The value of reducing uncertainties in global land cover with respect to climate change mitigation policy assessment. Value of Information Workshop. Washington DC, 28 June 2010.
- Fritz, S., See, L.M., Rembold, F., 2010b. Comparison of global and regional land cover maps with statistical information for the agricultural domain in Africa. *International Journal of Remote Sensing* 25 (7–8), 1527–1532.
- Fritz, S., You, L., Bun, A., See, L.M., McCallum, I., Liu, J., Hansen, M., Obersteiner, M., 2010c. Cropland for Sub-Saharan Africa: a synergistic approach using five land cover datasets. *Geophysical Research Letters* 38, L04404, 6 pp.
- Fritz, S., See, L., McCallum, I., Schill, C., Perger, C., Obersteiner, M., 2011a. Building a crowd-sourcing tool for the validation of urban extent and gridded population. *Lecture Notes in Computer Science* 6783, 39–50.
- Fritz, S., See, L., McCallum, I., Schill, C., Obersteiner, M., van der Velde, M., Boettcher, H., Havlik, P., Achard, F., 2011b. Highlighting continued uncertainty in global land cover maps to the user community. *Environmental Research Letters* 6, 044005.
- Google, 2010. About Google Earth: understanding Google Earth imagery. Available at: <http://earth.google.com/support/bin/answer.py?hl=en&answer=176147> (accessed 01.03.11).
- Google, 2011. Personal communication with Tanya Keen, 4 Mar 2011.
- Goodchild, M.F., 2008. Commentary: whither VGI? *Geojournal* 72, 239–244.
- Haklay, M., 2010. How good is volunteered geographical information? A comparative study of OpenStreetMap and Ordnance Survey datasets. *Environment and Planning B* 37, 682–703.
- Haklay, M., Singleton, A., Parker, C., 2008. Web Mapping 2.0: the neogeography of the GeoWeb. *Geography Compass* 2 (6), 2011–2039.
- Haklay, M., Basiouka, S., Antoniou, V., Ather, A., 2010. How many volunteers does it take to map an area well? The validity of Linus' law to volunteered geographic information. *The Cartographic Journal* 47 (4), 315–322.
- Hansen, M., DeFries, R., Townshend, J.R., Carroll, M., Dimiceli, C., Sohlberg, R., 2006. Vegetation Continuous Fields MOD44B, 2001 Percent Tree Cover, Collection 4, University of Maryland, College Park, Maryland, 2001.
- Hansen, M., DeFries, R.S., Townshend, J.R.G., Carroll, M., Dimiceli, C., Sohlberg, R.A., 2003. Global percent tree cover at a spatial resolution of 500 meters: first results of the MODIS Vegetation Continuous Fields algorithm. *Earth Interactions* 7 (1), 1–15.
- Herold, M., Mayaux, P., Woodcock, C.E., Baccini, A., Schmullius, C., 2008. Some challenges in global land cover mapping: an assessment of agreement and accuracy in existing 1 km datasets. *Remote Sensing of Environment* 112, 2538–2556.

- Howe, J., 2008. *Crowdsourcing: Why the Power of the Crowd is Driving the Future of Business*. Crown Business, New York.
- Khatib, F., DiMaio, F., Foldit Contenders Group, Foldit Void Crushers Group, Cooper, S., Kazmierczyk, M., Gilski, M., Krzywda, S., Zabranka, H., Pichova, I., Thomson, J., Popovic, Z., Jaskolski, M., Baker, D., 2011. Crystal structure of a monomeric retroviral protease solved by protein folding game players. *Nature Structural & Molecular Biology* 18, 1175–1177.
- Leung, D., Newsam, S., 2010. Proximate sensing: inferring what-is-where from georeferenced photo collections. In: *Proceedings of the IEEE International Conference on Computer Vision and Pattern Recognition*. IEEE CS Press, pp. 1–8.
- Loveland, T.R., Belward, A.S., 1997. The IGBP-DIS Global 1 km land cover data set, DISCover first results. *International Journal of Remote Sensing* 18 (5), 3289–3295.
- Marris, E., 2010. Birds flock online. *Nature*. doi:10.1038/news.2010.395.
- Newman, G., Zimmerman, D., Crall, A., Laituri, M., Graham, J., Stapel, L., 2010. User-friendly web mapping: lessons from a citizen science website. *International Journal of Geographical Information Systems* 24 (12), 1851–1869.
- Open Geospatial Consortium Inc., 2004. Geospatial portal reference architecture, OGC-04-039, version 2. http://portal.opengeospatial.org/files/?artifact_id=6669 (accessed 11.11.10).
- Pittman, K., Hansen, M.C., Becker-Reshef, I., Potapov, P.V., Justice, C.O., 2010. Estimating global cropland extent with multi-year MODIS data. *Remote Sensing* 2 (7), 1844–1863. doi:10.3390/rs2071844.
- Quaife, T., Quegan, S., Disney, M., Lewis, P., Lomas, M., Woodward, F.I., 2008. Impact of land cover uncertainties on estimates of biospheric carbon fluxes. *Global Biogeochemical Cycles* 22, GB4016. doi:10.1029/2007GB003097.
- Ramankutty, N., Evan, A.T., Monfreda, C., Foley, J.A., 2008. Farming the planet: 1. geographic distribution of global agricultural lands in the year 2000. *Global Biogeochemical Cycles* 22, GB1003. doi:10.1029/2007GB002952.
- Schurmann, N., 2009. The new Brave NewWorld: geography, GIS, and the emergence of ubiquitous mapping and data. *Environment and Planning D: Society and Space* 27, 571–580.
- Terrametrics, 2010. Support: Terrametrics and Google Earth. Available at: http://www.truearth.com/support/faqs_content_google.htm (accessed 01.03.11).
- Timmer, J., 2010. Galaxy Zoo shows how well crowdsourced citizen science works. <http://arstechnica.com/science/news/2010/10/galaxy-zoo-shows-how-well-crowdsourced-citizen-science-works.ars> (accessed 31.01.11).
- Turner, A.J., 2006. *Introduction to Neography*. O'Reilly Media Inc, Sebastopol CA.
- Voinov, A., Bousquet, F., 2010. Modelling with stakeholders. *Environmental Modelling and Software* 25 (11), 1268–1281.