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LAND-USE CHANGE DATA IN CLIMATE CHANGE ASSESSMENTS: CHALLENGES AND OPPORTUNITIES

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NOTE BY THE SECRETARIAT

This paper has been prepared by Professors Peter H. Verburg, Kathleen Neumann and Linda Nol, Wageningen University, the Netherlands. It discusses the challenges and opportunities presented by land-use change data in climate change assessments and models.

The document is declassified under the consultants' responsibility and does not necessarily reflect the views of the OECD or its member countries.

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EXECUTIVE SUMMARY

1. Land use and land cover data play a central role in assessments related to climate change and emission inventories. These data originate from different sources and inventory techniques. Each source of land use/cover data has its own domain of applicability and quality standards. Generally data are selected for climate change assessments without explicitly considering the suitability of the data for the specific application, the bias originating from data inventory and editing and the effects of the uncertainty in the data on the results of the assessment.

2. The most common land use/cover data are derived from remote sensing images and survey/census data. While remote sensing data are generally characterized by a high spatial and temporal resolution they fail to identify the use and management of the land. Due to resemblances of the reflectance of different land cover types the uncertainty in information is often related to the level of thematic disaggregation and the land cover type of interest. Census or survey data are mostly focused on the agricultural sector and may largely deviate between countries in terms of definitions of land use classes and inventory techniques. However, they may provide a valuable source of data on land management highly relevant to climate change assessments.

3. Besides the domain of applicability of the different data sources careful attention needs to be paid to potential bias introduced as result of temporal and spatial aggregation of the data. Straightforward aggregation operations may lead to unintended bias in the data. Selection of appropriate data resolution for analysis and aggregation procedures should depend on the characteristics of the landscape under study and the features of interest. Comparison of data from different sources is often hampered by differences in definition of land/use cover classes. Because of differences in the intended application of the data and the regional context widely diverging definitions are used for similar land use/cover types. Moreover, many changes in land use and management are not observable from land cover data which may lead to an underestimation of change and impacts.

4. Acknowledging the different information contained in the different data sources and the causes of inconsistencies between data, several methods have been developed to better use existing data and to document the information and uncertainties in the different data. A number of studies have combined remote sensing data and census/inventory data to use the strengths of both data sources. Mostly the area estimates and details about land use are derived from the inventory/census data while the spatial distribution is based on remote sensing data. These data sets are a frequent source of data for model applications in climate change related studies. At the same time a wide range of specific techniques is available to better compare and integrate different data and make optimal use of the information available. Such techniques include the use of *e.g.* fuzzy logic or conceptual overlaps through semantic-statistical approaches. Improved validation techniques can contribute to accuracy assessments of different land cover data which assists in the selection of the data for a specific application. Finally, uniform systems for documenting the thematic information contained in land cover data will help to better judge the contents and specific application domain of the data.

5. The conclusions of this study are based on an inventory of possible approaches to improve the way in which climate change assessments select and use land use and land cover change data. These include:

- Awareness of data inconsistencies and uncertainty
- Documentation of classification systems of land use and land cover data
- Careful selection of data given the specific application requirements
- The use of appropriate scaling and aggregation methods
- Combination of different data sources to optimize information content
- Collect new additional data for validation and improvement of coverage of regions and land cover types with high level of uncertainty
- Specific attention for the representation of land use systems and mosaics within land use/cover data

1. Introduction: the importance of land use and land cover change for climate change impact assessments

6. Land use and land cover change are one of the prime driving forces of changes in the Earth system and climate in particular. Agricultural land uses are estimated to contribute to changes in atmospheric concentrations of greenhouse gases (GHG) – non-CO_2 greenhouse gases account for 10-12% of the total global anthropogenic emissions (2007). At the same time agricultural lands generate very large CO_2 fluxes both to and from the atmosphere, but the net flux is small. The expansion of crop lands and pastures to the detriment of forests results in an increase in atmospheric CO_2. This decreases the sink capacity of the global terrestrial biosphere, and thereby may amplify the atmospheric CO_2 rise due to fossil and land-use carbon release. Besides the impact of land cover change on GHG emissions, changes in land management and land use practices can also largely affect emissions. Differences in forest management are likely to influence carbon emissions or sequestration in different ways (Schulp *et al*., 2008b) while agricultural management is known to largely influence emission strengths (Dendoncker *et al*., 2004). Methane emissions from rice fields are highly dependent on water management (Verburg and Denier van der Gon, 2001) and rice variety choice (Denier van der Gon *et al*., 2002)

7. Land use and land cover change not only impacts GHG emissions but also land surface properties of relevance to climate. At the global scale, changes in land surface properties associated with changes in vegetation can have impacts on continental and global atmospheric circulation, with possible large impacts on regional and continental climate (Pielke *et al*., 1998). At local to subnational, national and regional scales, the impacts of land cover changes on surface radiation budgets, surface hydrology, surface energy balance and surface friction are not straightforward bur rather complex. Micro- to mesolevel impacts of land use/cover change upon climate include remote impacts upon local circulation regimes. They can be labeled land use driven 'teleconnections' where changed ecosystem characteristics affect, for example, local weather or livelihood conditions such that effects are communicated to regions distant from actual changes in surface characteristics (Eastman *et al*., 2001).

8. Often the impact of land use and land cover change on climate change is studied from the perspective of land use/cover change as a driver of climate change (Schulp *et al*., 2008a). However, in many cases the interrelations are more complex. Land use and land cover change can also be induced by

climatic changes. Droughts have strong effects on vegetation and may increase the risk on forest fires. Climate change may also make areas more or less suitable for certain land use management practices leading to changes in land use decisions. Multi-directional impacts may be linked through feedbacks that strengthen or attenuate the interaction between land use/cover change and climate change. Such feedbacks make it difficult to distinguish impacts from drivers (Bossel, 1999). Large-scale deforestation changes climate conditions and, hence, influences vegetation patterns and occurrence of forest fires. These may affect land requirements and reclamation potential (Carvalho *et al*., 2004; Foley *et al*., 2003; Nepstad *et al*., 2001). Such feedbacks can also act through the socio-economic system: intensified land use practices can lead to higher income which, in turn, can trigger investments in further intensification or expansion of the farmed area. It is important to distinguish between positive (amplifying) and negative (attenuating) feedbacks. Positive feedbacks are self-reinforcing and concern interactions between the effects and drivers of land use change that amplify the effect of these changes (Lambin *et al*., 2003). Unsustainable use of the soil after deforestation may lead to a higher rate of future deforestation as a consequence of soil degradation. Negative feedbacks are found when the effects of land use change attenuate further change: the response of environmental degradation following deforestation may lead to innovative and more sustainable land conversions, slowing down the rate of forest conversion. Some feedbacks result in a gradual modification of the land use system, while others result in a sudden change or system collapse when the system has reached a threshold or point of no return.

9. A feedback that deserves special attention is the adaptation of land management in response to climate change. Adaptation aims at reducing the potential negative consequences of climate change through adapting management practices in such a way that they anticipate on the changed climatic conditions. Adaptation may include a wide variety of measures (EEA, 2008). These range from spatial planning measures to restrict new residential locations in areas with high flooding risk to the use of improved crop varieties that are better adapted to the changed climatic conditions (Polsky and Easterling III, 2001). Underlying the design of measures of climate change adaptation is a careful analysis of the vulnerability of the land system to climate change. Methods for vulnerability assessment are currently in rapid development to make such assessments possible (Polsky *et al*., 2007; Schröter *et al*., 2005).

10. Excellent overviews of the interactions between land use and land cover change and the climate system are provided by the Millenium Ecosystem Assessment (MEA, 2005) and the Global Environment Outlook (UNEP, 2007).

11. Given the very central role of land use and land cover change almost all assessments related to climate change somehow make use of data on land use/cover. These data may originate from different sources and inventory techniques. Each source of land use/cover data has its own domain of applicability and quality standards. This report aims at identifying critical issues related to the use of land use and land cover data in climate assessments. Based on an inventory of data sources the domain of applicability and the constraints of particular datasets are discussed (section 2). Review of literature reveals large uncertainties and inconsistencies in land use/cover data. These may have critical implications for climate change assessments. Therefore an overview of possible errors and inconsistencies is provided (section 3) as well as methods and techniques that may reduce such errors and inconsistencies (section 4). The implications for climate change assessments and integrated assessment models are described in Section 5. The report ends with a section listing the main conclusions for using land use/cover data in climate studies.

2. Inventory of data types on land use/cover available

2.1 Remote sensing data

12. Land use and land cover data may be derived from different sources based on multiple methods for observation and inventory. The most common source of data on land cover is remote sensing.

Remotely-sensed data include information gathered by aerial photography and satellites. Solar radiation (or in case of radar actively emitted radiation) is reflected from the surface of the earth—from soil, water, vegetation and building—to sensors that measure the intensity of different frequencies. Each type of surface reflects or absorbs different frequencies. Based on these measurements it is possible to make inferences about what is on the surface of the earth. In principle this information is restricted to land cover. The reflection is related to the cover of the earth surface which not always reveals the intended use of the land. However, land cover in combination with the spatial pattern of land cover and additional attributes may allow, to some extent to derive land use from remote sensing data. Park and Stenstrom (2008) subdivide urban land cover from remote sensing data into several land use classes based on the dominant use of the area. They indicate that when combined with non-spectral information high accuracies in classifying (urban) land use can be achieved.

2.2 Survey and census data

13. Another commonly used source of land use/cover data are surveys and census data. Many countries and international agencies collect statistical information on land use. Agricultural land use types are often reported as part of an agricultural census. Besides area cultivated with specific crops such information often also includes management information such as irrigation, fertilizer application rates and crop yields. Similarly, forestry statistics may provide information about harvesting practices etc. Therefore, census information is highly suitable to provide land use information which can never be collected through remote sensing. A major drawback is that census information is often derived from a sample of individual (household) observations and reported on the level of administrative units given privacy considerations. Therefore the spatial precision of the information is often limited. Another drawback is that most information is focused on economic sectors and information on (semi-)natural land uses is often not included.

14. Besides remote sensing and census information other, but less frequently used, sources of land use and land cover data include maps based on observations, participatory maps (Rambaldi *et al.*, 2007) and cadastral information (Aspinall, 2004). An overview of the characteristics of different sources of land use and land cover data is given in Table 1.

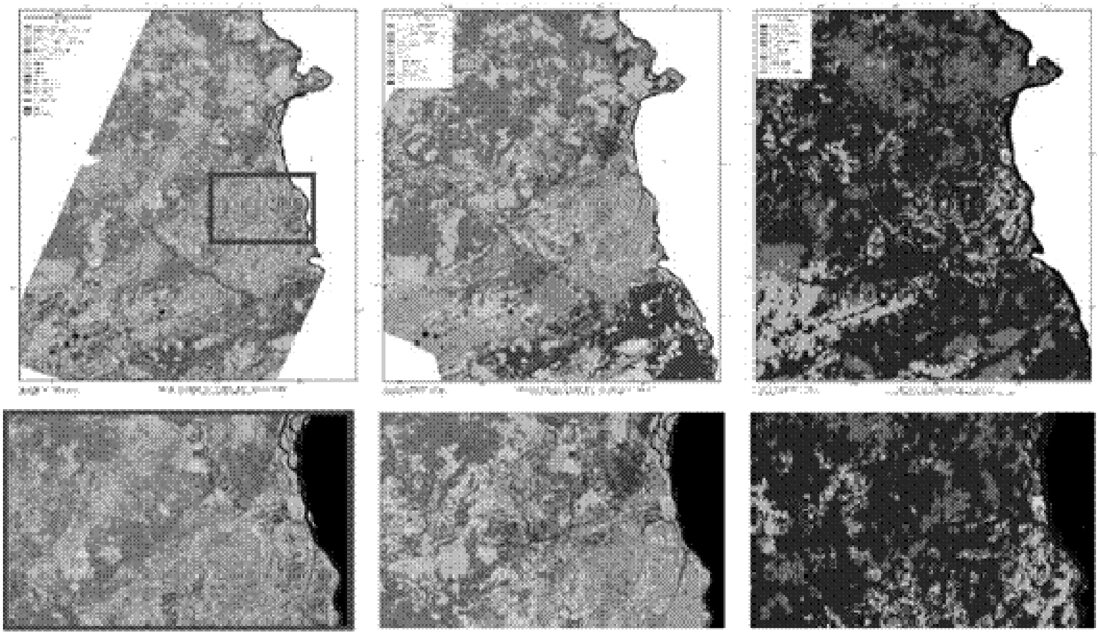
2.3 Applicability domain of data in relation to data characteristics

15. It is important to notice that the different sources of data have clearly different applications. High resolution remote sensing data based on sensors including IKONOS and Quickbird offer highly detailed information about land cover and the possibility to infer land use information. However, acquisition and interpretation of such data is only feasible for relatively small areas and may be very costly. Therefore, global land cover datasets based on remote sensing data are using medium to coarse resolution sensors, *e.g.* in case of the GLC2000 dataset (www-tem.jrc.it/glc2000/) use was made of SPOT images (1 km resolution) while the recent GLOBCOVER data (http://ionia1.esrin.esa.int/index.asp) are based on MERIS images from ENVISAT with a spatial resolution of 300 meter. Figure 1 provides an illustration of the consequences of differences in spatial resolution for the resulting land cover map.

Table 1. Overview of the spatial, temporal and thematic properties of various sources of land use and land cover data

Data source	Spatial resolution	Spatial extent	Temporal resolution	Temporal extent	Thematic properties
Remote Sensing	0.6 meter – 1 km depending on sensor	Dependent on sensor. Coverage is limited in case of clouds (not for radar)	Frequent depending on sensor/satellite	Depending on launching and life time of sensor. Few remote sensing data are available before 1970's except for aerial photographs	Land cover classes. Classification is based on sensor characteristics and user preferences
Census/survey data	Administrative units	Often national level	Infrequent depending on census, often less than every 10 years	Country specific depending on statistical system	Focus on economic sectors (mostly agriculture and forestry)
Traditional land use maps	Dependent on scale of mapping	Varying	Often made for one year only	-	Varying
Participatory maps	Dependent on scale of mapping	Often restricted to territory of one or more communities	For one year only	-	Depending on purpose of mapping
Cadastral information	Very precise information	Dependent on cadastral system	Continuously updated	Often available for long time period	Limited to tenure conditions with limited information about land use, especially in urban environments

Figure 1. Illustration of the effect of the spatial resolution of remote sensing data on the patterns of land cover identified



Landsat ETM+ (30 m)
mosaic of 3 images
Time period 1999-2000

ENVISAT MERIS FR (280 m)
July 2003

SPOT5 VGT (1 km)
Time period 1999-2000

Source: http://www.esa.int/esaEO/SEMGSY2IU7E_index_1.html

16. The spatial resolution of the data also affects the type of information that can be derived as well as the resulting land areas reported. Normally each pixel is classified as one specific land cover type. In a situation with land cover types that occur at relatively low prevalence or in small patches the occurrence of these land cover types may be underestimated because they will not dominate the reflectance characteristics of the pixel. Moody and Woodcock (1994) show that large proportion errors can arise as landscapes are represented at increasingly coarse scales. Additionally, the direction and magnitude of these errors appear to vary as a function of both the spatial pattern of the land-cover classes and the spatial resolution. Therefore, the appropriate spatial resolution of the sensor may depend on the landscape under analysis (Ozdogan and Woodcock, 2006). Various methods are developed to correct to some extent for this aggregation problem either through statistical techniques (Marceau and Hay (1999) and Moody and Woodcock (1995)provide an overview of possible methods) or through unmixing of the spectral information in the pixel during the interpretation.

17. Whereas the prior discussion on spatial scale effect is mostly concerned with raster data a similar effect can be found in polygon representations of land use data. An important generalisation mechanism inherent to polygon maps is the *minimum mapping unit* (MMU), *i.e.* the minimum size (or sometimes width, when referred to elongated units) that a land parcel must exceed in order to be represented in the map. Isolated land use units having a size below this threshold are aggregated into the surrounding unit. Afterwards, there is no trace in the map of the smaller units. An exception is the case of *mosaic polygons*, which have a compound label representing a mosaic of patches from different classes, all smaller than the MMU. In this kind of polygons, the percentage cover from each class may be reported, but information

regarding their actual distribution within the polygon is missing as a parsimonious exchange for clarity (Castilla and Hay, 2007).

18. Besides these issues related to spatial scale, temporal scale is also important. Remote sensing data offer the best possibility to monitor changes in land cover through time. However, cloud cover may cause problems in large parts of the humid tropics during a considerable part of the year. Radar images or new, advanced, sensors may overcome these problems to some extent. Survey and census data tend to be infrequent and sampling schemes and definitions tend to change between surveys. Time series based on remote sensing, however, tend to suffer from inconsistencies due to improved resolution of sensors and changes in classification scheme. Moreover, accuracies of classification are often around 80% while change in land cover over the period analyzed is often smaller. Therefore, interpretations that ensure temporal consistency by focusing on change rather than providing two individual interpretations for the different years are essential (Berberoglu and Akin, 2009; Hansen *et al*., 2008). In this case the changes in spectral signature are linked to changes in observed land cover. These relations are used to map changes directly. Figure 2 gives an example of this method for forest loss monitoring in the Congo basin.

3. Differences and consistency of land use and land cover data

19. The previous section has indicated that different sources of land use data may provide information on different aspects of land use and land cover. Comparison and integration of different data sources is however hampered by different issues including:

- temporal consistency
- spatial consistency and scaling bias
- thematic differences and inconsistencies
- difference between land cover and land use

The following paragraphs will discuss the underlying reasons for consistency problems in more detail and provide a number of illustrations.

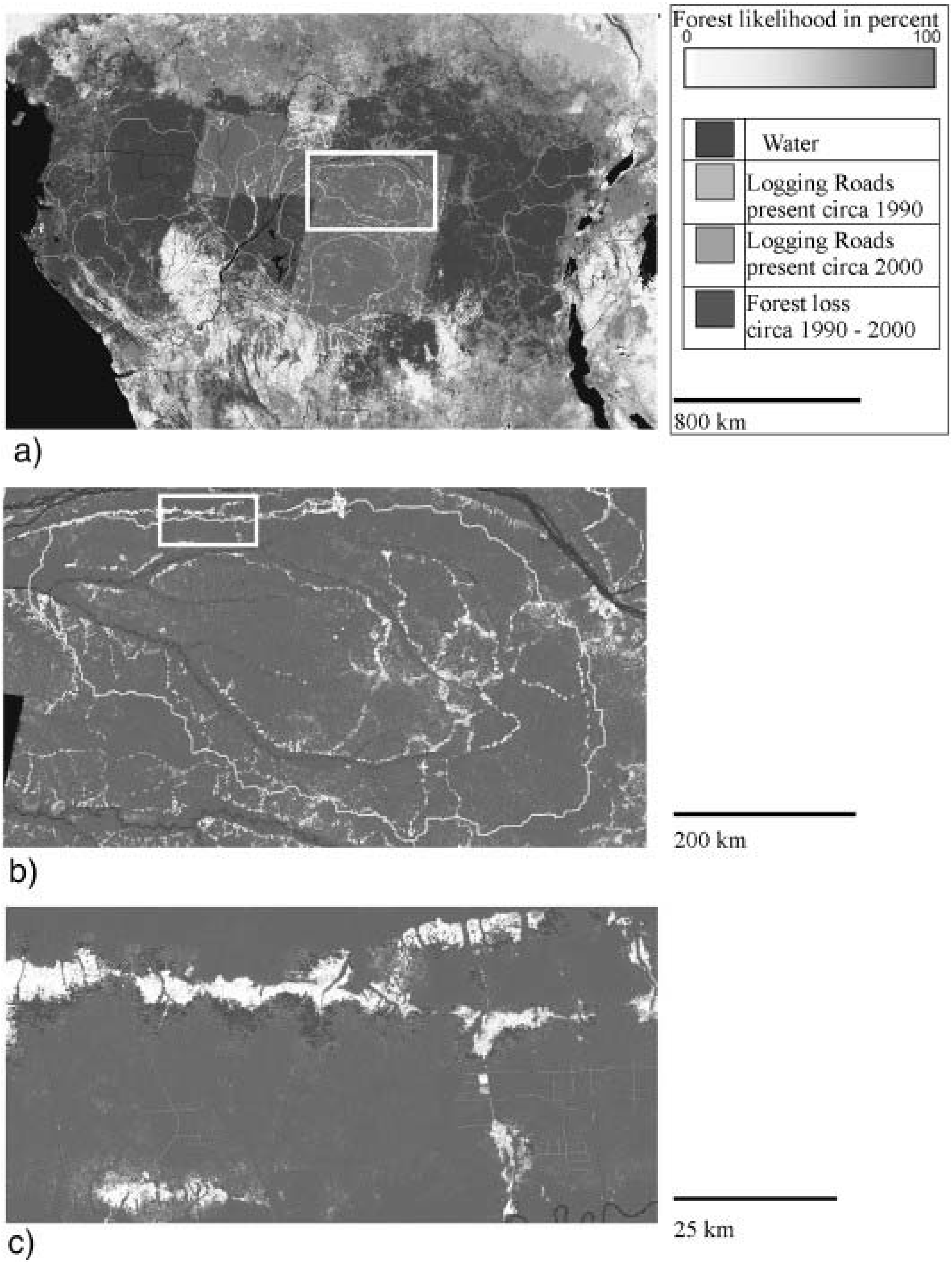
3.1 Temporal consistency issues

20. For monitoring and analysis of change in land use/cover it is essential to have consistent data over a longer period of time. Preferably these are derived from exactly the same data source with exactly similar processing techniques. However, often this is not possible. The production of higher level spatial data sets from remote sensing has often been driven by short-term funding constraints and specific information requirements by the funding agencies. As a result, a wide variety of historic data sets exist that were generated using different atmospheric correction methods, classification algorithms, class labelling systems, training sites, map projections, input data and spatial resolutions. Because technology, science and policy objectives are continuously changing, repeated natural resource inventories rarely employ the same methods as in previous surveys and often use class definitions that are inconsistent with earlier data sets (Wadsworth *et al*., 2008). Remote sensing sensors have changed in time and interpretation techniques have become more advanced. Often it is not a very attractive option to use out-dated techniques and data sources to provide data on land use. Besides these issues many interpretations of remote sensing data include a ‘supervised’ component in which classification decisions and generalizations are made by an expert. This is not necessarily the same person as the one that has processed the data for an earlier year. Re-interpretation of data of previous years using similar techniques and interpreters is often not feasible.

21. Also for survey and inventory data techniques may change in time, including classification systems, legend classes and spatial detail. When analyzing time series of data it is important to distinguish

changes caused by inconsistencies between the data sets and the ‘real’ changes. In practice, these are often difficult to separate.

Figure 2. Forest likelihood and forest change map for Maringa–Lopori–Wamba, Sangha Tri-National, and Salonga–Lukenie–Sankuru CARPE landscapes, where a) is Congo Basin overview with MODIS map in grayscale, b) is a zoom on the Maringa–Lopori–Wamba product, and c) is a full-resolution zoom on a locale in the north of this landscape



Source : Hansen *et al*., 2008.

3.2 Spatial consistency issues

22. Spatial inconsistencies between data sources may be, to some extent, related to positional errors. Positional errors can be cause by georeferencing of remote sensing data or the level of generalization of a vector map in which complex boundaries between two land use types are summarized by a simplified vector (Castilla and Hay, 2007). If georeferencing is appropriately done such inconsistencies are small as compared to inconsistencies as result of differences in spatial scale and aggregation. Nol *et al*. (2008) present a series of land cover data from different sources for the same area, part of the fen meadow landscape in Western Netherlands. The landscape is dominated by meadows with a large number of small, linear, waterbodies (ditches). Table 2 provides an overview of the characteristics of the different data sets used which range from detailed mapping in the field to a European-wide dataset based on remote sensing data. Figure 3 shows the differences in spatial representation of this landscape for the different data sets. Obviously, the less detailed data do not represent the linear figures of the landscape and grassland cover dominates in the coarse scale datasets. These differences in representation which relate to spatial resolution and minimum mapping unit have large consequences for the land use statistics that can be derived from the data. While grassland only covers 77% of the area and water covers 11% of the landscape in the data based on field mapping, the CLC2000 map classifies 100% of the area as grassland. Such difference may have large impact on the estimation of land use services and emissions of greenhouse gases.

Figure 1. Figure 3. Representations of polder Zegveld using differrent land cover databases

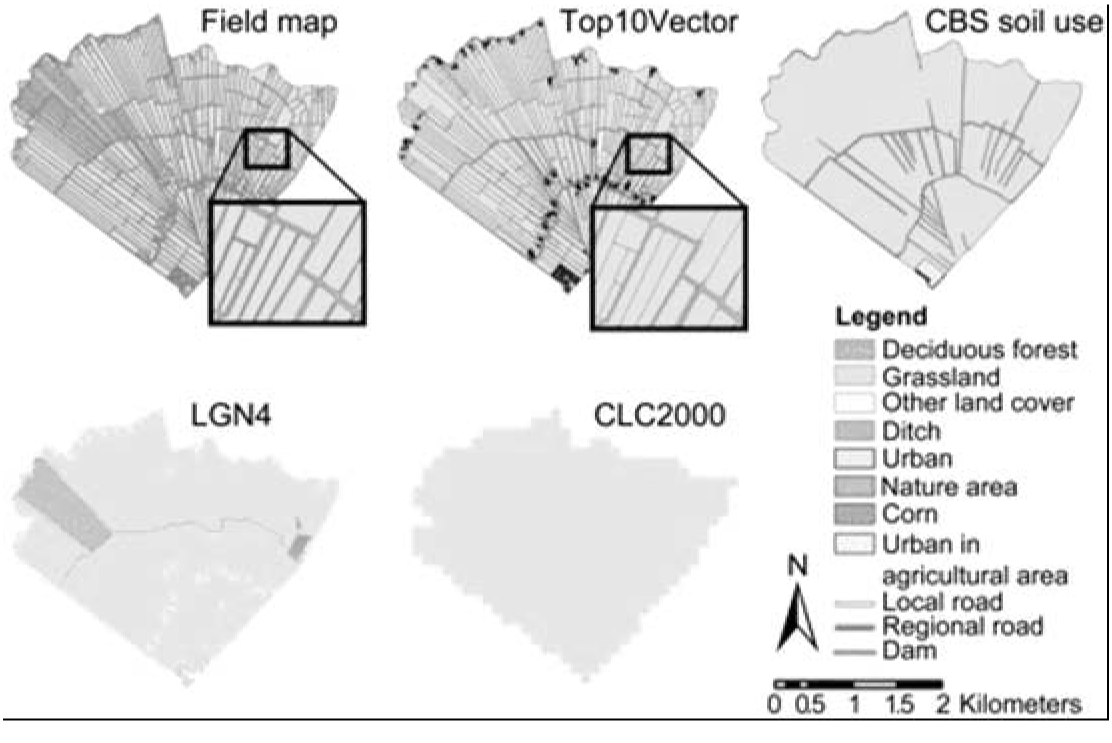


Table 2. Characteristics of land cover databases

Database	Type	Year of validity	Minimum mapping unit	Grid cell size	Projection	Extent	Number of categories	Source
Field map	Vector	2006	0.2 m (ditch) 2 m (roads)	–	RD[b]	Polder Zegveld	12	(Nol *et al.,* 2008)
Top10 Vector	Vector	2000–04	3 m (ditch) 2 m (roads)[a]	–	RD[b]	Netherlands	50	(TDN, 2006)
CBS soil use	Vector	2000	10 000 m^2[c]	–	RD[b]	Netherlands	38	(CBS, 2002)
LGN4	Raster	1999-2000	5 000 m^2	25m	RD[b]	Netherlands	39	(GeoDesk, 2006)
CLC2000	Raster	2000	250 000 m^2	100m	Lambert Azimuthal	Europe	43	(EEA, 2000)

a (Vliegen, 2000)
b RD = Dutch National Grid
c Except for roads and railroads, which are all included in the database.

23. In another study Fassnacht *et al.* (2006) found the class "broadleaf trees" which forms narrow linear features along rivers in the landscape studied, to be particularly susceptible to changes in resolution. This is comparable to the findings for linear water bodies by Nol *et al.* (2008). Ozdogan and Woodcock (2006) also noted that large landscape elements can support large pixels, but when the landscape elements of interest are small, fine resolution is needed to correctly estimate surface areas. In many landscapes linear or other small land cover types may have important impacts on the provision of ecosystem services or have strong influence on the functioning of the hydrological and climatic system.

24. Spatial inconsistencies may also originate from improper aggregation of the data to the level of analysis. Especially remote sensing data are often provided at a relatively high spatial resolution. For all kinds of assessments aggregations are made. The level of aggregation and the aggregation method are extremely important determinants of the resulting land use distributions and spatial configurations. Dendoncker *et al.* (2008) compared differences in landscape composition and configuration between three cell class assignment (aggregation) methods and three spatial resolutions. Differences between aggregation results were found to be at least as large as the differences between the results of widely diverging scenarios. This study, as well as a similar study by Schmit *et al.* (2006) demonstrated the importance of the rasterization method and the level of aggregation as a contribution to uncertainty when developing future land use and land cover scenarios and in analyzing landscape structure in ecological studies. Methods that are frequently used for aggregating high-resolution data are (1) selection based on the majority of the underlying pixels, (2) the central point method and (3) a method that constraints the majority based allocation based on the prevalence of the different land use types at the regional level. Each of the three methods has its specific strengths and weaknesses in aggregating data. The majority based aggregation leads to a strong change in the prevalence of the land use types at the regional level as result of underrepresenting smaller land use types that are spatially distributed in small patches. The central point method selects the land use type at the centre of the aggregated grid cell as the land use type representative for the larger grid cell. Overall this method keeps the prevalence of the land uses more similar but has a strong impact on the spatial pattern of the land use map. The constrained method is very suited if the prevalence of the different land use types should be maintained although bias in spatial patterns may occur. The spatial bias introduced due to aggregation is strongly dependent on the landscape type and level of analysis. In most studies aggregation methods are arbitrarily chosen and hardly ever reported.

3.3 Thematic differences and inconsistencies

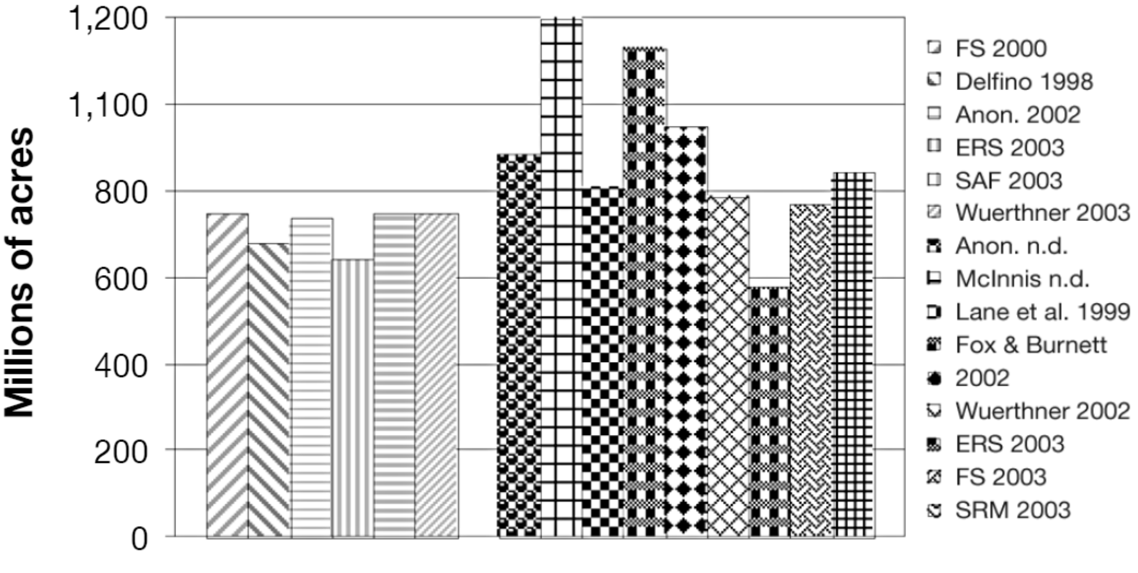
25. Different data sources have different capacities in capturing specific land use/cover types given the specific characteristics of the observation technique. Each data source will therefore lead to specific categorical uncertainties. Categorical uncertainty is inversely related to the degree of confidence we can have about whether the plot of terrain corresponding to a given map unit is actually devoted to the use/cover indicated in the map. This uncertainty is commonly assessed using a contingency table of agreement between predicted and observed values, typically referred to as the confusion matrix (Castilla and Hay, 2007). Comparisons of data sources for similar areas have identified that some land use/cover types are, independent of the data source, are easier to delineate than other land use/cover types. For an area in Hessen, Germany (Bach *et al.*, 2006) compared the performance of three different datasets on land use/cover for a small area in which accurate field information was available. In the analysis, the following six land-use classes were considered: urban and traffic areas, forest, water, arable land, pastures and meadows, and fallow land (including other uses). The results showed that the congruency of the land-use classes forest and urban and traffic areas is higher than the congruency of the land-use classes of the open land (arable land, pastures and meadows, fallow). A similar conclusion was reached by an analysis of global land cover maps at 1 km spatial resolution by Herold *et al.* (2008). The existing global land cover maps at 1 km spatial resolution have arisen from different initiatives and are based on different remote sensing data and employed different methodologies. The authors harmonized the thematic legends of four available coarse-resolution global land cover maps (IGBP DISCover, UMD, MODIS 1-km, and GLC2000)

using the LCCS-based land cover legend translation protocols. Analysis of the agreement among the global land cover maps and existing validation information highlights general patterns of agreement, inconsistencies and uncertainties. The thematic classes of Evergreen broadleaf trees, Snow and Ice, and Barren show high producer and user accuracy and good agreement among the datasets, while classes of mixed tree types show high commission errors. Overall, the results show a limited ability of the four global products to discriminate mixed classes characterized by a mosaic of trees, shrubs, and herbaceous vegetation. There is a strong relationship between class accuracy, spatial agreement among the datasets, and the heterogeneity of landscapes.

26. In another comparison between different datasets for the same area Neumann *et al*. (2007) identify that comparison of different datasets using a similar legend is hampered by differences in the thematic content of the classes between maps. Interpreters have often used dissimilar definitions of land use/cover classes and used different aggregation schemes. Differences in thematic content are also a direct result of the specific purpose for which a data set was constructed.

27. A wide range of definitions are used for the same land cover class between different data sets and inventories. Wadsworth *et al*. (2008) present an overview of the canopy cover needed to classify a land cover as forest according to official definitions of multiple data (based on an inventory of Gyde Lund). The definition of what is a forest covers the full range of canopy cover between 10% and 80%. Therefore land use/cover data based on different definitions may widely vary. The situation is, however, worse for grasslands as was already identified in the earlier mentioned comparisons. Figure 4 gives an example of forest and rangeland areas in the United States based on different studies (taken from Lund, 2004). Rangeland areas clearly deviated much more than forest area estimates.

Figure 4. Recent published estimates of forest (striped) and rangeland (chequered) area in the United States (taken from Lund, 2004)



28. Estimates of the Earth’s land surface covered by rangelands vary from 18% to 80% in an inventory of studies (Lund, 2007). This wide range of variation is due to differences in estimates of the land surface (inclusive or exclusive ice covered surface etc.), data source and the definitions used. Large inconsistencies in the definition of rangelands are also a result of the lack of an international organization responsible for the assessment and reporting on the world’s rangelands as there is for the periodic global forest assessments by FAO (Lund, 2007). The classification of rangelands is especially troublesome in case of sparse tree cover, such as in savannahs. If separate definitions of forest and rangeland are used that are

not mutually exclusive there is a risk of double-counting or underestimating the respective areas with major implications for the assessments based on these numbers.

3.4 Land cover versus land use

29. Another issue underlying differences in area reported is the distinction between land use and land cover. Several studies have identified the relation of land cover and land use as one of the major challenges for monitoring, modelling and communicating land change (Comber, 2008; Verburg *et al.*, 2009). Land cover addresses the layer of soils and biomass, including natural vegetation, crops and human structures that cover the land surface. Land cover is thus directly observable, both in the field as well as from remote sensing images. Land use in contrast refers to the purposes for which humans exploit the land cover (Fresco, 1994; McConnell and Moran, 2001). Land use is not always easily observable, although, in many cases, land use may be inferred from observable activities (*e.g.* grazing) or structural elements in the landscape (*e.g.*, the presence of logging roads). When different land uses are systematically linked through either temporal (*e.g.* crop rotations) or spatial interactions we are dealing with land use systems. An example of the effects of the differences in land cover and land use definition is the documentation of the process of land abandonment at the European scale. While agricultural statistics indicate strong decreases of agricultural areas these are, in many cases, not observed in data derived from remote sensing. One of the reasons for not being able to observe the ongoing changes in land use by remote sensing is the use of 'abandoned' grasslands for other functions of which especially boarding horses is very important in peri-urban areas where former farmland is used for horse-boarding and horse-riding facilities ('horsification'). Although the land cover in these areas remains the same this has large implications for the functioning of the land and the rural economy. Because in many countries hobby-horses are not included in agricultural statistics the extent and areas used for this type of land function are largely unknown. Other alternative uses of abandoned land include all kinds of hobby-farming. Also outside the peri-urban areas of Europe the process of land abandonment is poorly represented in land cover data (Haines-Young and Weber, 2006). Many authors have reported large declines of agricultural areas in Europe's mountain areas (Etienne *et al.*, 2003; MacDonald *et al.*, 2000; Tasser *et al.*, 2007). These mountain areas are facing two related trajectories of change: part of the meadows are more intensively used, while other parts have been converted to pasture or have been abandoned (Mottet *et al.*, 2006). These changes in intensity and the actual use of the grasslands, either for pasture or hay-making is not observable by remote-sensing but can have large implications for the vegetation and botanical composition (Hochtl *et al.*, 2005; Tasser *et al.*, 2007).

4. Methods and opportunities to deal with data inconsistencies

30. The inconsistencies between the different datasets outlined in the previous section have now been acknowledged by many authors. At different levels solutions are provided to deal with these inconsistencies and make optimal use of the different data sources. This section will discuss a number of methods and improved data management possibilities that explicitly address the inconsistencies and uncertainties of the different land use and land cover data.

4.1 Combining different data sources to establish new land use and land cover databases

31. The acknowledgment of differences in datasets and the possible complementarities between different datasets has provided the incentive to various incentives to prepare harmonized datasets. Table 3 provides a, non exhaustive, overview of a number of such datasets prepared at the global level. Many of the datasets combine (sub)national census data with remote sensing information. (Ramankutty *et al.*, 2008) assume that the inventory data is the "truth" (except for identified outliers), and use the satellite data to spatially disaggregate these inventory data within each administrative unit. This way the strength of the ground observations used to generate the inventory data is combined with the high spatial detail of remote

sensing data. However, given the use of inventories from various, national level census and other inventories there is a risk of inconsistent definitions of the agricultural and especially the grassland classes between countries leading to a globally inconsistent map. Remote sensing products often use a consistent interpretation globally. However, area estimates from remote sensing data tend to deviate strongly due to uncertainties in the interpretation of the spectral reflectances.

32. Similar integration techniques have been used for individual countries or continents, *e.g.* Hurtt *et al.* (2001) integrated land use statistics and remote sensing data to generate a land use map for the US while Cardille and Foley (2003) combined remote sensing and census data to estimate land cover change in the Brazilian Amazon. For climate change studies the history of land cover change is also interesting. Historic data are even more difficult to get. Therefore several attempts have been made to reconstruct historic land use based on sparse data of human population, potential vegetation and model assumptions. Examples of global land cover reconstructions include (Klein Goldewijk, 2001; Pongratz *et al.*, 2008; Ramankutty and Foley, 1999; Wang *et al.*, 2006).

Table 3. Overview of the main characteristics of a number of harmonized, global datasets for land cover based on the combination of different individual land cover products

Method	Reference	Thematic coverage	Spatial resolution	Time period
Remote sensing and (sub)national inventory data	(Ramankutty and Foley, 1998)	Croplands	5 min	1992
Remote sensing and (sub)national inventory data	(Monfreda *et al.*, 2008; Ramankutty *et al.*, 2008)	Croplands, grasslands, 175 crop types	5 min	Circa 2000
National level census data and available thematic spatial datasets	(Erb *et al.*, 2007)	Cropland, grazing, forestry, urban, transportation	5 min	2000
FAO national statistics, IGBP DIScover, Global Land Cover 2000 (GLC2000)	(Goldewijk *et al.*, 2007)	Cropland and grasslands	5 min	1990-2000
Satellite imagery, ecological modeling, country surveys, existing maps of potential land cover and layers of the major anthropogenic land covers	(Sterling and Ducharne, 2008)	Cropland, built-up land, grazing land, wetlands, irrigated land, inundated land	5 min	1990-2000

4.2 Techniques for integration of different sources of land cover data

33. Instead of combining different land cover data into one consistent database it is possible to use different techniques to avoid the occurrence of inconsistencies through equalizing thematic and spatial content of the data or through change detection techniques. Other methods explore the information contained in data inconsistencies to detect land cover changes. This section lists a number of efforts from the literature towards a better integration of multi-source data.

34. Petit and Lambin (2001) present a methodology to integrate multi-source remote sensing data into a homogeneous time series of land cover maps in order to carry out change detection. In their paper the authors developed a method to increase the comparability between land cover maps coming from panchromatic aerial photographs and SPOT XS (multi-spectral) data by equalizing their levels of thematic content and spatial detail. By controlling successively the parameters that influence the level of map generalization, the equalization of the thematic content and of the level of spatial detail of the two land cover maps can be significantly improved. This confirms the hypothesis that map generalization can improve the integration of data coming from different sources.

35. Also the analysis of land cover change based on remote sensing data can be done in ways to limit the propagation of errors through the data interpretation process. Postclassification comparison is often used to detect land-cover changes between two images, *i.e.*, the change is identified based on a comparison of the interpreted land cover maps of time 1 and time 2. However, the accuracy of this change detection technique is only as good as the result of the multiplication of the accuracies of each individual classification. Studies have identified image differencing as being the most accurate change detection technique (Macleod and Congalton, 1998; Petit *et al*., 2004; Ridd and Liu, 1998). The difference between two images is calculated by finding the difference between each pixel in each image, and generating an image based on the result. This image is interpreted with or without the help of observations on the ground to generate a map of land cover change. This method avoids the detection of change as result of differences in interpretation of the individual images.

36. Wadsworth *et al*. (2008) present another method for making best use of information from different land cover maps to detect land cover change. These authors present a method utilising aspects of quantified conceptual overlaps and semantic-statistical approaches (Comber *et al*., 2005). The method is applied to reconcile three independent land cover maps of Siberia, which differ in the number and types of classes, spatial resolution, acquisition date, sensor used and purpose. A map of inconsistency scores is presented that identifies areas of most likely land cover change based on the maximum inconsistency between the maps. The method of quantified conceptual overlaps was used to identify regions where further investigations on the causes of the observed inconsistencies seem warranted. The method highlights the value of assessing change between inconsistent spatial data sets, provided that the inconsistency is adequately considered.

37. A common approach to address the problem of classification uncertainty in remote sensing and GIS data is using fuzzy logic (Fritz and See, 2005; Hagen, 2003; Jung *et al*., 2006; Robinson, 2003; Woodcock and Gopal, 2000). Jung *et al*. (2006) present a straightforward method that merges existing land cover datasets into a desired classification legend for a specific application. This process follows the idea of convergence of evidence and generates a 'best-estimate' data set using fuzzy agreement. The authors apply the method to develop a new joint 1-km global land cover product (SYNMAP) with improved characteristics for land cover parameterization of the carbon cycle models that reduces land cover uncertainties in carbon budget calculations. The overall advantage of the SYNMAP legend is that all classes are properly defined in terms of plant functional type mixtures, which can be remotely sensed and include the definitions of leaf type and longevity for each class with a tree component. See and Fritz (2006) have used fuzzy logic to incorporate expert knowledge for comparing the GLC2000 and the MODIS land cover product. To capture classification uncertainties of both data sources the authors mapped spatial disagreement by using a combination of fuzzy logic and expert knowledge. Fuzzy membership matrices were generated based on knowledge of classification experts to indicate the different levels of difficulty in classifying different land cover types and to map spatial disagreement. The areas of highest disagreement were validated using additional land cover information and a hybrid land cover map was generated by fusion of the GLC2000 and the MODIS land cover product (Fritz and See, 2005; See and Fritz, 2006).

38. Others have developed methods specifically aimed at integrating local or regional data. Pelorosso *et al*. (2009) present a method to combine remote sensing and census data for a region in Central Italy. Alfieri *et al*. (2007) propose a reclassification method to better assign the various parameters needed for land surface model simulations in a case study in south-eastern Kansas, USA. Besides land use/land cover data sets normalized difference vegetation index (NDVI) measurements, elevation and slope are used to provide a more accurate dataset. The authors recommend this method especially for local scale simulations.

4.3 Standardization and harmonization of land cover data

39. The previous section introduced a number of methods to deal with the limited compatibility and comparability between different land cover datasets and their thematic legends. Other efforts aim at improving the flexibility and usability of land cover data to avoid that users need to make a translation of the different classification systems to allow for comparability of different data sets (Neumann *et al*., 2007).

40. The above presented efforts on combining and integrating different land cover datasets demonstrate the need to harmonize land cover data and classification systems. International initiatives, such as the Group on Earth Observation (GEO), the Global Terrestrial Observing System (GTOS), and the Global Observation of Forest and Land Cover Dynamics (GOFC-GOLD), foster the establishment of international standards and protocols with respect to standardized development and harmonization of land cover data (Herold, 2006). These initiatives are largely driven by needs of international conventions (GCOS, 2004; GEOSS, 2005). An example of an already established strategic and methodological framework for harmonization of land cover classification systems is the UN Land Cover Classification System (LCCS) (Gregorio, 2005; Jansen and Gregorio, 2002). The LCCS applies flexible but standardized set of classifiers and thresholds and is currently evolving as an internationally agreed standard for land cover characterization (Herold, 2006). Comparable land cover classification systems and understanding of semantic differences between datasets is essential for comparative accuracy analyses of different land cover datasets. Harmonization and validation of land cover data are therefore often parallel processes.

4.4 Improved validation of land use and land cover data

41. Validation can help the user to select the most appropriate land cover or land use map for a specific purpose based on its correspondence with field observations or other data of relevance to the specific study for which the land use/cover data are prepared. Classical validations use field observations to judge the suitability of land cover data. Mostly these compare ground observations of land cover with the information in the land cover database and the percentage of correctly represented observations is measured. Frey and Smith (2007) use a large set of ground based observations to see if global and regional land cover products are suitable for climate and ecosystem assessments. Field observations require an enormous investment, especially in case of the validation of global datasets. Therefore, Iwao *et al*. (2006) propose the use of Degree Confluence Project (hereby DCP) information as a new method for validating land cover maps. The DCP is a volunteer-based project that aims to collect onsite information from all the degree confluences (intersections of integer level latitude and longitude gridlines) in the world. The paper of Iwao *et al*. (2006) assesses the reliability and effectiveness of DCP-derived data in validating land cover maps. DCP-derived validation information (at 749 confluences) was used to evaluate existing land cover maps for Eurasia (GLC2000, MOD12, UMD, and GLCC). The agreements between the DCP-derived validation information and the land cover maps were between 50 and 58%.

42. The uncertainty in global land cover product is further illustrated in a paper of Frey and Smith (2007) who used a collection of 2161 geolocated, irregularly spaced field observations of land cover throughout West Siberia to validate a number of currently available global land cover characteristics databases (including the Global Land Cover Characteristics database derived from Advanced Very High

Resolution Radiometer data (GLCC.AVHRR), the Global Land Cover Classification derived from Moderate Resolution Imaging Spectroradiometer data (GLCC.MODIS), the Global Lakes and Wetlands Database (GLWD) and the West Siberian Lowland Peatland Database (WSLPD)). The study indicated that overall agreement with ground observations of land cover is between 11 and 21% only. Permanent wetlands and waterbodies are underestimated in all databases, agreement with the ground data is only 2% for the GLCC.MODIS, 23% for GLCC.AVHRR, 45% for GLWD and 57% for WSLPD. Agreement with open water bodies is even poorer (0-5%). These results raise into question the efficacy of incorporating currently available land cover products into terrestrial ecosystem models in northern wetland environments.

43. In the absence of a consistent global database of field observations Sterling and Ducharne (2008) validate their global land cover maps by comparing the areas of land cover with a wide range of estimates from the literature. The comparison, based on estimates of anthropogenic land cover show a wide variation in the percentage of the earth surface covered by anthropogenic land cover indicating the high degree of uncertainty in global maps. Based on these observations the authors highlight the need for improvements on land cover mapping. Especially the area and distribution of grazing land needs to be determined more accurately given its large influence on land surface processes. Similar attention is needed to map global tree plantations given the large importance and dynamics of timber plantations in North America and oil-palm plantations in Southeast Asia.

44. Wu *et al*. (2008) use a similar comparison of global data products to estimate the validity of the global products for depicting croplands in China. These authors conclude that coarse scales of representation of heterogeneous landscapes are a major reason for inaccuracies in cropland distribution and recommend better dealing with these heterogeneous landscapes in land cover products. The same conclusions were reached in a similar study by Xiao *et al*. (2003).

5. Implications for climate change analysis/modeling

5.1 Land cover data and emission inventories

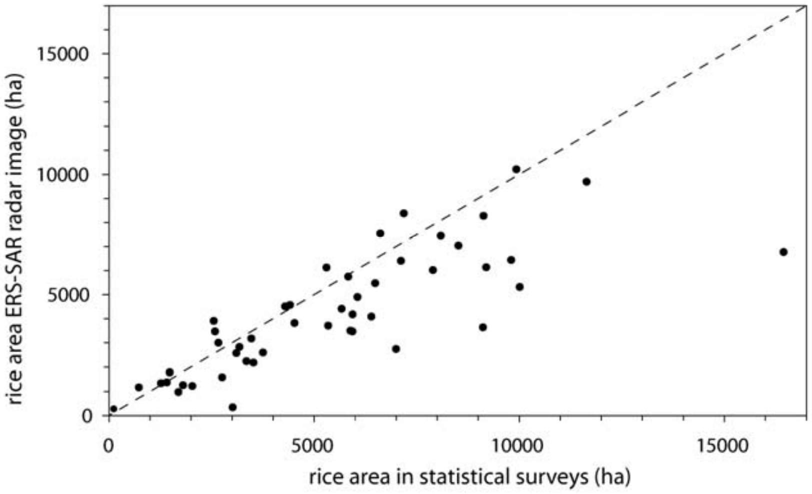
45. The choice of data to be used in emission inventories may have large consequences for the resulting emission estimates. Verburg *et al*. (2006) made an assessment of the uncertainties involved in regional estimates of methane emissions from rice fields in one of the main rice growing regions of the Philippines. The rice area in the wet season determined by supervised classification of the ERS-SAR image. A comparison between the rice area derived from the ERS-SAR image and the rice area given in the statistical surveys at the level of municipalities, shown in Figure 5, shows large deviations between the two sources for a number of municipalities. In general, the rice grown area as identified by ERS-SAR is smaller than the area reported in statistics (almost 30% for the total study area). There can be several causes for this difference:

- Inconsistency in statistical sources; statistics by the National Statistical Office differ considerably from those by the Bureau of Agricultural Statistics (Philrice/BAS, 1995) and statistics by the provincial offices of the Department of Agriculture.

- Differences between the years of reporting in statistics (1991) and the ERS-SAR image (1995). However, in time series of the Bureau of Agricultural Statistics, there is no major difference in total rice area between these years.

- Interpretation and classification problems of the ERS-SAR image. Many rice fields are relatively small and irrigation canals and dykes are abundant. These small elements can cause an underestimation of the rice area in the ERS-SAR interpretation. It is clear that the regional emission calculated with the rice area of the ERS-SAR is considerably lower than the emission calculated with the statistical data. In comparison to other uncertainties such as model accuracy and upscaling procedure the uncertainty in emission estimates as result of uncertainty in land cover data is highest.

Figure 5. Rice area per municipality based on interpretation of Radar images and as reported in statistical surveys (Verburg *et al.*, 2006)



46. Earlier in this report the influence of the spatial resolution of the land cover maps on the areas of respectively meadows and waterbodies in the Dutch Fen Meadow landscape was discussed. Nol *et al.* (2008) assessed the impact of the spatial resolution of the land cover data for emissions of nitrous oxide from this region. Based on the estimated surface areas agricultural N_2O emissions were estimated using different inventory techniques. All four common databases overestimated the grassland area when compared to the field map. This caused a considerable overestimation of agricultural N_2O emissions, ranging from 9% for more detailed databases to 11% for the coarsest database. The effect of poor land cover representation was larger for an inventory method based on a process model than for inventory methods based on simple emission factors. Although the effect of errors in land cover representations were, in this study, small compared to the effect of uncertainties in emission factors, these effects are systematic (*i.e.*, cause bias) and do not cancel out by spatial upscaling. Moreover, bias in land cover representations can be quantified or reduced by careful selection of the land cover database.

47. Quaife *et al.* (2008) show how the use of different land cover maps influences calculated large-scale, bottom-up estimates of terrestrial carbon fluxes. The authors compare calculated fluxes based on globally available moderate resolution satellite-derived land cover maps with fluxes calculated using a reference high (25m) resolution land cover map specific to Great Britain (the Land Cover Map 2000). The authors demonstrate that uncertainty is introduced into carbon flux calculations by (1) incorrect or uncertain assignment of land cover classes to PFTs (Plant Functional Types), (2) information loss at coarser resolutions, (3) difficulty in discriminating some vegetation types from satellite data. Differences in land use data account for differences between -15.8% to 8.8% in calculated Gross Primary Production.

48. The role of land cover data in calculating emissions is especially important in case of the reporting requirements for greenhouse gas inventories to the IPCC commission. Countries individually report their land use (changes) to the IPCC commission. To make these country specific reporting as much

comparable as possible, guidelines and best practice documents were developed[1]. These guidelines address many of the issues raised in this report regarding proper use of the data with respect to harmonization of legends, scaling issues and other uncertainties. However, these guidelines actually contain little information on how to estimate land areas (changes) and leave it to the individual countries to select the land cover data used from a variety of sources (agricultural census surveys, forest inventories, and remote sensing data). Although this approach enables countries to make best use of existing data inconsistencies between data sources will ultimately lead to inconsistent estimates of emissions that are not easily corrected.

5.2 Considerations with respect to integrated assessment modelling

49. Many models used in global climate studies (*e.g.* ORCHIDEE (Krinner *et al*., 2005) and LPJ (Bondeau *et al*., 2007)) use Plant Functional Types as a basis for simulating vegetation dynamics. Sterling and Ducharne (2008) indicate that the reclassification process of land cover type to plant functional types and especially assigning a percentage of bare soil to the land cover types is an important step in land surface modeling. The percentage of bare soil drives the major land surface fluxes and properties, determining, among others, LAI and albedo. Wang *et al*. (2006) present a table to convert land cover classes to Plant Functional Types using available information to make the Plant Functional Types as consistent with the land cover description as possible but also mention that this translation could be another source of uncertainty given the wide range of Plant Functional Types possible in one land cover type.

50. An important concept used for integrated assessment modeling are the agro-ecological zones (AEZs) originally developed by the FAO and further developed to the global database of AEZs in cooperation with the International Institute for Applied Systems Analysis (IIASA) (Fischer *et al*., 2002). The AEZ approach combines different sources of land data and land evaluation methods with socioeconomic and multiple-criteria analysis to evaluate spatial and dynamic aspects of agriculture. The land cover data used are based on the Global Land Cover Characterization product based on AVHRR source imagery dates from April 1992 through March 1993. The AEZ approach provides the basis for several applications including identification of areas with biophysical constraints to crop production, estimation of the extent of potential agricultural land, quantification of crop productivity considering farming technology and management, and impact assessment of climate change on agricultural productivity and food production (www.iiasa.ac.at/Research/LUC/Papers/gaea.pdf). Unfortunately most applications do not account for the characteristics of the data on which this approach is based. Better consideration of the strengths and limitations of the approach may lead to a better use of these data in applications.

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[1] See: http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf_files/Chp2/Chp2_Land_Areas.pdf for the full guidelines with respect to the estimation of land cover areas.

51. Besides the GAEZ approach also other integrated assessments of land use change, climate change and environmental impacts use different sources of land cover and land use data. Many assessments use a series of coupled models. In such models often a module specifically dealing with land change is found. This module converts the demands for commodities and services into change in land cover areas. These land cover changes are allocated within a spatial representation of the landscape (*e.g.*, (Rounsevell *et al.*, 2005; Sohl *et al.*, 2007; Verburg *et al.*, 2008)). Demands for commodities are often determined by (multi-)sectoral approaches and are expressed in the units of the goods or service under consideration, such as agricultural production (Meijl *et al.*, 2006). The conversion into land cover change is not always straightforward. In case of agricultural commodities farming system characteristics such as multiple-cropping, intercropping and other management practices need to be accounted for. Expansion of arable area is only one possible way of fulfilling an increasing demand for agricultural commodities. In many cases intensification by means of increasing inputs, efficiency or cropping intensity are a more likely means of fulfilling the demand. Similar considerations apply to forestry. Increasing wood demands do not necessarily lead to deforestation but in many cases to forest degradation or changed management practices which are difficult to detect using remote sensing (Lambin, 1999). Most land change models focusing on deforestation are only capable of addressing complete deforestation and ignore forest degradation (Nelson and Geoghegan, 2002). Demands for recreation can only be directly linked to land cover as far as these concern special facilities such as camp sites or attraction parks. However, most recreation takes place as part of a multiple functionality of the land depending on the attractiveness of the landscape and nearness to tourist attractions.

52. The difficulty in translating demands for commodities and services in land cover claims becomes even more apparent when the demands are based on economic (commodity) models while the spatial allocation is based on spatially explicit land cover change models (Verburg *et al.*, 2008). Economic modeling approaches traditionally rely on agricultural census data with a strong link to the actual land use practices. Most spatial land cover change models are using land cover maps based on remote sensing as a starting point (*e.g.*, (Evans and Kelley, 2008; Pontius *et al.*, 2001; Wu *et al.*, 2006). Coupling models therefore means explicitly dealing with inconsistencies between data sources and the difference between land use and land cover.

5.3 Synthesis

53. The wide variety of inventory and modeling approaches makes it difficult to synthesize the current state of land use and land cover data in the different approaches. Table 4 provides an attempt to summarize the strengths and weaknesses in different approaches mentioned in the previous sections.

Table 4. Overview of the strengths and weaknesses of current practices of applying land use and land cover data in emission inventories and modelling

Application domain of land use/cover data	Context	Strengths	Weaknesses	Recommendation
Emission inventories	IPCC	Best use of existing data and supplementary new data Guidelines for dealing with inconsistencies	High likelihood for inconsistencies between countries Possibility to manipulate emission inventories through data selection	Evaluation of practices of different countries/parties and refinement of reporting guidelines
Emission inventories	Various research projects	Use of advanced methods/models to provide improved emission estimates	Focus on emission processes and little attention for uncertainty in land use/cover data selection and use	More attention for the role of land use/cover in emission inventories
Land-surface modelling	Various research projects	Clear identification of the crucial role of land cover in climate change research	Various problems with the translation of land cover/use data in model environment	More attention for correctly using land use/cover information in model environment and translation of land cover into plant functional types
Integrated assessment modelling	Various research projects	Link between land related commodities, land use and land cover	Problems in linking land use and land cover data; potential for inconsistent use of data	Elaboration of the linkages between land use and land cover using different data sources

6. Conclusions

1. Awareness of data inconsistencies and uncertainties is essential

54. Uncertainty assessment is an integral part of many climate change studies. The complexity of the processes investigated and the sensitivity of outcomes to model assumptions and model parameters make an uncertainty analysis difficult. In most analysis the uncertainty and error in the land cover data used as input to the assessments is not addressed. Several studies have indicated that land cover data have high uncertainties. Because part of the errors and uncertainties in land cover data may be structured towards under- or overestimating a specific land cover type due to observation or aggregation bias this may lead to a one-directional error in the climate change assessments. It is especially this type of errors and uncertainties that should be given explicit attention in climate change assessments.

55. Differences between different data sets representing land use or land cover are often seen as inconsistencies or errors. However, in many cases such differences are the result of different representations of the data in terms of classification and temporal and spatial scale. An analysis of the underlying reasons for inconsistencies and errors will help to make more appropriate use of the data in climate change assessments. Inconsistencies between data may, in fact, indicate that complementary information is available which, if properly used, may benefit the overall assessment.

56. A proper selection of the data is useful for all assessments. In many climate change assessments land use and land cover data are just regarded as input variables for which easily available data are used without explicit consideration of alternative data sources. This often results in a mismatch between the characteristics of the data and the use of the data in further calculations. Models calibrated with point or field level data will, most likely, not perform optimally with coarse scale data.

57. The risks involved in allowing countries to make best use of available data for their emission inventories could be reduced by better documenting the potential bias involved in selecting a specific data source for the inventory. Enhanced guidelines could assist in identifying potential bias in inventories to make estimates more comparable between countries.

58. Many climate change assessments focus on improving model performance and representation. Given the uncertainties involved in land use and land cover data and the key role of these data in climate change assessments a better balance of research efforts between input data and model representation should be achieved.

2. Documentation of classification system of land use and land cover data is essential

59. For a proper selection of data on land cover and land use and their intended application it is essential to have a clear and extended documentation of the land use or land cover classes. Especially in translating the land cover information to plant functional types, common in land surface modeling, this information is essential. Given the wide variety of definitions of the same class used in different maps it is not wise to use data without a proper documentation of the categories involved. In spite of many efforts to create uniform descriptions of classes a wide variety of definitions exists. This variety also reflects the diverse intended applications of the collected data and, in many cases, the categories are defined to best suit the application the data are collected for.

60. A proper documentation of land use and land cover data can best be made in a uniform system. The FAO LCCS system (www.glcn.org/) provides guidelines and software for this and is now accepted by many users as a proper means for documenting and exchanging documentation on land cover classifications.

3. Select data based on needs for a specific application

61. Land cover and land use information is often confused and not explicitly distinguished. Most information currently used in climate change assessments is based on remote sensing and primarily contains land cover information. However, for many climate change assessments management aspects of the land cover are essential. Land use may be very different on the same land cover. Grasslands may be natural, intensively managed or extensively used with highly different implications for *e.g.* carbon sequestration. Often land use is therefore directly inferred from land cover information which is not appropriate. Carefully combining land use information from inventories with land cover information from remote sensing may be a means to better distinguish land cover and land use information. Appropriate use of the differences with land use and land cover data depending on the needs of the specific application will enhance the assessment quality.

62. It is common belief that land use and land cover data with high spatial resolution are the ‘best’ data. This is not always the case. Thematic resolution or fit of the land cover classes with the model description of the processes under investigation may be more important criteria for data quality for a specific application. Selection of land use and land cover data should therefore primarily be based on the match of the data with the model or assessment approach rather than on the characteristics of the data itself.

63. Several studies have indicated the poor fit of global data on land use and land cover to specific regions. The classification algorithms and categories considered in global studies are not targeted towards the specific regional conditions. Therefore the use of global land use and land cover data for regional climate change assessments should be avoided. Regional specific data often better represent the regional situation and are therefore better suited for this level of analysis.

4. Use appropriate scaling and aggregation methods

64. Most studies require edits to the data prior to analysis. Such edits may include thematic aggregations, geographic projections or spatial aggregations. Such changes to the data may influence the characteristics of the data and the information contained in the data. Proper documentation is essential but often lacking.

65. Spatial aggregations may be done by different methods with different effects on the data. Some aggregation methods lead to an overall loss of information while other aggregation methods can structurally change the representation of specific classes in the data depending on the prevalence and structure of the classes in the landscape. Different landscapes may require different aggregation techniques. Methods are available to correct unintended bias due to aggregation. Careful documentation of the aggregation methods and its effects on the data is essential.

5. Combine different data sources when complementary information is available: data integration

66. Collecting new data using improved protocols is a straightforward solution to the shortcomings of current data on land use and land cover. However, data collection is extremely expensive and time consuming, especially at national to global scales. Several attempts of integrating different, complementary data sources, mentioned in the previous sections, have provided high quality results as well as assessments of the uncertainty of the different data sources. By combining the strengths of different data more robust and reliable data can be constructed. In many countries and regions multiple data sources that are not yet explored as common sources of land cover data are available and could be used to improve remote sensing derived land cover estimates or census based land use inventories. Examples of such data include for the European Union the Farm Accountancy Data Network (FADN) which was established to monitor the effects of the EU common agricultural policy (CAP). The services responsible in the Union for the operation of the FADN collect every year accountancy data from a sample of the agricultural holdings in the European Union. Derived from national surveys, the FADN contain harmonized micro-economic data, *i.e.* the bookkeeping principles are the same in all countries. Holdings are selected to take part in the survey on the basis of sampling plans established at the level of each region in the Union. The methodology applied aims to provide representative data along three dimensions: region, economic size and type of farming. This type of data can potentially improve insights in the land use practices that land cover data cannot provide. Because of privacy issues the location of the sample points is not disclosed, which largely restricts the applicability of these data (Fais et al., 2005). Another useful dataset at the European level are for obtaining additional land use/cover data is the LUCAS “*Land Use/Cover Area frame statistical Survey*" pilot project which was launched by Eurostat (the European statistical bureau) in 2001. In contrast to mapping approaches this project uses area frame sampling to collect data. Based on the visual observation

of sample geo-referenced points, area estimates are computed and used as a valid generalisation without studying the entire area under investigation. The approach has also the important advantage of not involving/disturbing the land owners and the farmers. At European level currently around 250,000 points have been samples providing an excellent coverage of ground observations. A third example of alternative existing datasets that may provide useful information on land use are parcel registration systems. In the European Union such databases are part of the IACS integrated control system designed to administrate and control EU subsidy applications, veterinary events and national environmental regulations. Although such data are not always publicly available several authors have successfully applied this database for research purposes (Schmit *et al.*, 2006; Lucas et al., 2007)

67. Ground observations are an important source to evaluate and validate land use/cover products. Combination of remote sensing data and ground data will both improve the classification as well as validate the quality of the land cover product. An example of extensive work combining ground observations and remote sensing data for the US is presented by Loveland *et al.* (2002). In this work for a large number of sample blocks historical Landsat Multispectral Scanner (MSS), Thematic Mapper (TM), and Enhanced Thematic Mapper Plus (ETM+) satellite images were used to interpret land cover change for each sample block on five separate dates (nominally 1973, 1980, 1986, 1992, and 2000). Historical aerial photographs from roughly equivalent times are used as ancillary information sources. The sample block land cover data were used to analyze the spatial, temporal, and sectoral dimensions of change and identify and document the forces driving land cover change using field observation, socio-economic data analysis, and a synthesis of published literature. A full discussion of the project methodology is given in Loveland *et al*. (2002).

68. This type of data integration efforts will enhance the use of existing data using the complementarities of the differences in different data sources.

6. Collect new data with common inventory techniques

69. In addition to making most efficient use of existing data new data need to be collected to improve the representation of land use and land cover in climate assessments. For newly collected data documentation of methods and uncertainty (including validation) should receive sufficient attention. Documentation of the classification of data should follow internationally agreed guidelines. A possible system for documenting information on the land cover classification is the FAO LCCS system. Other systems documenting a similar amount of information may be of equal suitability. For global scale applications new land cover data should focus on the main uncertainties in current data. Most important is the representation of grassland areas. Global estimates are deviating largely between current sources. Also the distinction between forest and forest plantations deserves explicit attention. Well organized campaigns aimed at a combination of remote sensing with ground observations and inventory data may improve the representation of grasslands and forest plantations in global land cover datasets.

7. Pay more attention to mosaics and distinguish land use systems

70. Most land cover data attempt to classify each pixel by the dominant land cover. For very high resolution data this may be possible. In medium to coarse resolution data this representation may lead to problems since many landscapes contain a mosaic of land cover types. Although the classification into one dominant land cover type is convenient in many models and other applications the characteristic conditions of these mosaic landscapes are disregarded. In terms of processes relevant to climate change mosaics landscape can have specific characteristics that may not be represented correctly by the dominant land cover types. Therefore, the explicit representation of these mosaics as separate classes in land cover data should be considered.

71. Besides land cover information land use information is often essential to properly inform climate change assessments. However, the same land use may represent differences in the interaction of humans with the environment depending on the local context including cultural aspects of land management and environmental conditions. Instead of representing the landscape in terms of land cover and/or land use a representation in terms of land use systems that integrate the land cover and management aspects may be considered. Ellis and Ramankutty (2008) have attempted to map land use systems, in their terminology called anthropogenic biomes (or anthromes). Each of these biomes shares a common level of interactions between humans and the environment, examples include 'dense settlements', 'pastoral villages' and 'populated rainfed croplands'. Each of these biomes consists of a heterogeneous landscape mosaic combining a variety of different land covers. Through some of this heterogeneity might be explained by the relatively coarse resolution of the analysis, a more fundamental explanation is that human-environment interactions lead to different mosaics due to natural variation in terrain, human enhancement of the natural heterogeneity by concentrating activities at the most productive locations and heterogeneity caused directly by the specific activity types of the considered biome (Ellis and Ramankutty, 2008). Due to its focus on human-environment interactions the anthropogenic biomes are better proxies for the land functions of a particular location than land cover by itself. Besides the use of land cover (derived from Remote Sensing) and (agricultural) land use data (census data) also information concerning the spread of human population was used to construct the map. The human population maps are based on downscaled census data using remote sensing, road network and elevation data (Dobson *et al.*, 2000). The use an anthropogenic biome map instead of a conventional biome or land cover map has major advantages in land change science given the better representation of the human-environment interactions and its intensity that cannot directly be observed from land cover data (Ellis and Ramankutty, 2008). Since land functions are a direct result of human-environment interactions the anthropogenic biomes are closely linked to land functions, *e.g.* by indicating where land cover types are used for the production of commodities and where no primary goods are produced for human consumption ('wild lands'; [(Sanderson *et al.*, 2002]). Such a distinction could not easily be made based on the previously available global land cover maps.

GLOSSARY OF TECHNICAL TERMS[2]

ENVISAT	An Earth-observing satellite built by the European Space Agency (ESA) which was launched on the 1st March 2002. Envisat carries an array of nine Earth-observation instruments that gather information about the earth (land, water, ice, and atmosphere) using a variety of measurement principles.
ERS-SAR	The European Earth Resource Satellites (ERS)-1, 2 are established with a synthetic aperture radar (SAR) instrument to acquire images of ocean, ice and land regardless of cloud and sunlight conditions. Additional microwave instruments on-board ERS measure sea state, sea surface winds, ocean circulation, sea and ice levels, as well as the sea's surface temperature. ERS-SAR images have a spatial resolution of 30m.
Georeferencing	Determination of the spatial location of other geographical features in physical space, *i.e.* establishing its location in terms of map projections or coordinate systems. Examples include establishing the correct position of an aerial photograph within a map or finding the geographical coordinates of a place name or street address.
GLC2000	Global Landcover Classification for the Year 2000. GLC2000 has been derived from daily global images from the Vegetation sensor on-board the SPOT4 satellite. GLC2000 has a spatial resolution of 1km and discriminates between 22 land cover classes. The GLC2000 legend is based on the FAO Land Cover Classification System (LCCS).
IKONOS	A commercial earth observation satellite, and was the first to collect publicly available high-resolution imagery at 1- and 4-meter resolution. It offers multispectral (MS) and panchromatic (PAN) imagery.
LandSat ETM+	The Enhanced Thematic Mapper Plus (ETM+) instrument on-board the National Aeronautics and Space Administration (NASA's) LandSat satellite. LandSat ETM+ is a multispectral scanning radiometer with eight-band, capable of providing high-resolution imaging information of the Earth's surface (panchromatic band at 15m, multi-spectral bands at 30m). It detects spectrally-filtered radiation in visible and near infrared (VNIR), shortwave infrared (SWIR), and longwave infra-red (LWIR) and panchromatic bands from the sun-lit Earth.
LCCS	Land Cover Classification System of the Food and Agriculture Organization of the United Nations (FAO)/ United Nations Environment Programme (UNEP). LCCS provides a scale independent method for classifying land cover. The approach supports all types of land cover monitoring and enables a comparison of land cover classes regardless of data source, sector or country.

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[2] Most definitions in this glossary are based on Wikepedia.

MERIS	Medium Resolution Imaging Spectrometer. MERIS is one of the main instruments on-board the European Space Agency (ESA's) Envisat satellite. MERIS is operating in the solar reflective spectral range with 15 spectral bands. MERIS images have a spatial resolution of 300m.
MODIS	Moderate Resolution Imaging Spectroradiometer. MODIS is a key instrument on-board the National Aeronautics and Space Administration (NASA)'s Terra (EOS AM) and Aqua (EOS PM) satellites. MODIS captures data in 36 spectral bands and at varying spatial resolutions (2 bands at 250m, 5 bands at 500m and 29 bands at 1km).
PFT	Plant Functional Types. Representation of vegetation in land surface models. In the most general (and computatively efficient) mode, each average plant individual represents the entire regional population of a plant functional type
Quickbird	A high-resolution commercial earth observation satellite, owned by DigitalGlobe and launched in 2001. QuickBird collects the second highest resolution commercial imagery of Earth after WorldView-1, and boasts the largest image size and the greatest on-board storage capacity of any satellite. The satellite collects panchromatic (black & white) imagery at 60-70 centimetre resolution and multispectral imagery at 2.4- and 2.8-meter resolutions.
Raster	A data structure representing a generally rectangular grid of pixels, or points of colour, viewable via a monitor, paper, or other display medium. Raster images are stored in image files with varying formats
SPOT	A high-resolution, optical imaging Earth observation satellite system operating from space. SPOT was initiated by the CNES (Centre national d'études spatiales – the French space agency) in the 1970s.

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