→ 6th ESA ADVANCED TRAINING COURSE ON LAND REMOTE SENSING

Theory on Land Cover Land Use D3T1b

Mário Caetano

14–18 September 2015 | University of Agronomic Science and Veterinary Medicine Bucharest | Bucharest, Romania

In Land Cover Land Use studies, mot of the times, we are interested on Land Cover and Land Use characterisation through time

Land Cover and Land Use

Land Cover and Land Use Change Detection

The most used acronyms are

Land Use and Land Cover	Land Use and Land Cover Change	
LULC	**LULCC**	**e.g. IGBP**
Land Cover and Land Use	Land Cover and Land Use Change	
LCLU	**LCLUC**	**e.g. NASA, USGS**

Here we will use the acronyms **LCLU** and **LCLUC**.

There is a general tendency for evolving from **LCLU mapping** into **LCLU monitoring**, in order to somehow guarantee temporal consistency among LCLU maps for different moments in time.
(Fry et al., 2011).

Furthermore **LCLU monitoring** is a more inclusive term since it also includes LCLUC. This is true because most studies on LCLU monitoring also includes the identification and characterisation of changes.

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Summary

1 Setting the scene

2 The need for LCLU monitoring data

- LCLU: a cross-cutting environmental variable
- LCLU monitoring and environmental legislation
- Relation between two European initiatives (Copernicus and INSPIRE) and LCLU monitoring
- Hard and soft LCLU maps
- The Land Cover Classification System

3 From data to information: some important advances in LCLU monitoring

- Two different approaches for LCLU monitoring
- Spectral and class change detection
- Image classification for LCLU mapping

4 LCLU monitoring operational programs

- At country level (NLCD from USA)
- At European level (Land monitoring service within Copernicus)
- At Global level (GLOBCOVER)

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A definition of land…

“'A delineable area of the earth's **terrestrial surface**, embracing **all attributes of the biosphere** immediately above or below this surface, including:

• near surface climate,

• soil and terrain forms,

• surface hydrology including shallow lakes, rivers, marshes and swamps,

• near-surface sedimentary layers and associated groundwater and geohydrological reserves,

• plant and animal populations,

• human settlement pattern and physical results of past and present human activity (terracing, water storage or drainage structures, roads, buildings, etc.)."

Source: Interdepartmental working group on land use planning -FAO (2004)

Land cover *versus* Land use

Land cover (LC) - Physical and biological cover of the earth's surface including artificial surfaces, agricultural areas, forests, (semi-)natural areas, wetlands, water bodies.

Land use (LU) - Territory characterised according to its **current and future planned functional dimension** or **socio–economic purpose** (e.g. residential, industrial, commercial, agricultural, forestry, recreational).

Functional definition of LU
description of land in terms of its **socio-economic purpose** (e.g. agricultural, residential, forestry)

→ LU can be inferred from LC

Sequential definition of LU
description of land based on **series of operations on land**, carried out by humans, with the intention to **obtain products and/or benefits** through using land resources.

→ LU cannot be inferred from LC. Other information sources are needed.

Source: INSPIRE Directive

A possible LC classification

- Artificial surfaces
  - o Urban fabric
  - o Industrial, commercial and transport units
  - o Mine, dump and construction sites
  - o Artificial, non-agricultural vegetated areas
- Agricultural areas
  - o Arable land
  - o Permanent crops
  - o Pastures
  - o Heterogeneous agricultural areas
- Forests
- (semi-)natural areas
  - o Scrub and/or herbaceous vegetation associations
  - o Open spaces with little or no vegetation
- Wetlands
  - o Inland wetlands
  - o Maritime wetlands
- Water bodies
  - o Inland waters
  - o Marine waters

Source: INSPIRE Drafting Team "Data Specifications" (2007)

A possible LU classification

The ISIC system for LU classification
17 sections, 60 divisions, 159 groups and 292 classes

Agriculture, Hunting and Forestry
Fishing
Mining and Quarrying
Manufacturing
Electricity, Gas and Water Supply
Construction
Wholesale and Retail Trade, Repair of motor vehicles, motorcycles and Personal and household goods
Hotels and Restaurants
Transport, Storage and Communication
Financial intermediation
Real estate, Renting and Business activities
Public Administration and Defense, Compulsory social security
Education
Health and Social work
Other Community, Social and Personal Service Activities
Private Households with Employed Persons
Extra-territorial Organizations and Bodies

The 17 sections of the first level characterize main economic activities.

Source: ISIC - International Standard Classification of all Economic Activities

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The need for LCLU monitoring data

Hydrology

Biogeochemical cycles

Biodiversity

Climate change

Ecology

LCLU
The most important environmental variable

Natural disasters

Soil erosion

Epidemiology

Sustainability

Land management

The need for LCLU monitoring

Policy makers
(e.g. DG from EC, EEA, National Agencies)

Agencies responsible for policy implementation and enforcement

Research bodies

Users of LCLU information

Information providers

NGOs and the public

Industries and businesses that are often the target of policy

THE GLOBAL EARTH OBSERVATION SYSTEM OF SYSTEMS

GROUP ON EARTH OBSERVATIONS

Source: http://www.earthobservations.org

GEO area of societal benefits	Key land cover observations and desired products
Disasters: reducing loss of life and property from natural and human-induced disasters	• Fire monitoring (active+burn) • Surface cover type changes and land degradations due to disasters • Location of population and infrastructure
Health: understanding environmental factors affecting human health and well-being	• Land characteristics/change for disease vectors • Land cover/change affecting environmental boundary conditions • Demographic/socio-economic conditions and location and extent of settlement patterns
Energy: improving management of energy resources.	• Bio-fuel production sustainability • Biomass yield estimates (forestry and agriculture) • Assessments for wind and hydro power generation and explorations
Climate: understanding, assessing, predicting, mitigating, and adapting to climate variability and change.	• Greenhouse gas emissions caused by land cover change • Land cover dynamics forcing water and energy exchanges • Location and extent of energy consumption
Water: improving water resource management through better understanding of the water cycle.	• Land cover change affecting dynamics the hydrological system • Available water resources and quality Distribution of water bodies and wetlands • Water use pattern (*i.e.* irrigation, vegetation stress) and infrastructure
Weather: improving weather information, forecasting, and warning	• Land cover/change affecting radiation balance and sensible heat exchange • Land surface roughness • Biophysical vegetation characteristics and phenology
Ecosystems: improving the management and protection of terrestrial, coastal, and marine ecosystems.	• Changes in environmental conditions, conservation and provision of ecosystem services • Land cover and vegetation characteristics and changes • Land use dynamics and driving processes
Agriculture: supporting sustainable agriculture and combating desertification.	• Distribution and monitoring of cultivation practices and crop production (type, rotations, conditions) • Forest types and changes (*i.e.* logging) • Land degradations and threats terrestrial resources and productivity
Biodiversity: understanding, monitoring, and conserving biodiversity.	• Ecosystem characterization and vegetation monitoring (types, species) • Habitat characteristics and fragmentation of invasive and protected species • Changes in land cover and use effecting biodiversity

Source: Wulder et al. (2008)

The need for LCLU monitoring data

LCLU data

Landscape characterisation (composition, condition and dynamics)

Input for environmental models

As surrogate/proxies for other variables

- Atmospheric emissions in air quality models
- Potential for food production in models of food security
- Fuel availability in models of wildfire risk
- Ground permeability in flood risk models

Ultimately
LCLU data is important for policy on environment

- to help guide **policy formulation** and development
- to help **monitor and enforce** the implementation of these policies
- to **assess the impact** of existing or planned policies
- to maintain a watching brief in order to identify the **need for new policy** action

The need for LCLU monitoring data

EU Policy areas

- Environmental thematic strategies on urban environment, soil protection and sustainable use of natural resources;
- Reporting obligations under the **Water framework directive**, management of Natura2000 sites,
- **Environmental impact assessments** and reporting;
- Regional policies, territorial cohesion and European spatial development perspectives;
- **Common Agricultural Policy** (CAP);
- Common Transport Policy;
- EU Development Policies (i.e. sustainable development and poverty reduction, food security);
- Infrastructure for spatial information in Europe – INSPIRE and ESDI.

International Environmental Agreements

- the three Rio Conventions:
  - UN Framework Convention on Climate Change (UNFCCC) and its **Kyoto Protocol**,
  - **UN Convention to Combat Desertification** (UNCCD),
  - UN Convention on Biological Diversity (UNCBD),
- the UN-ECE Long Range Transboundary Air Pollution Deposition and dispersion modelling.

Other international conventions/agreements

- UN Forum on Forest with the related "FLEGT" policy whereby EU contributes to the transparency of the international timber market,
- **UN Millennium Development Goals**, where Goal I pledges to improve food and nutrition security,
- Ramsar Convention on Wetlands.

Source: IG-LMCS (2007)

GMES Global Land Working Group, 2008

LCLU information links to policies, reporting and assessment

- **Environmental reporting and assessments**
  - EURECA ecosystem service assessment (EEA) 2012
  - Land and ecosystem accounting (EEA / UNSD) annually
  - Land-cover Change (CORINE / LEAC) 2011
  - Astana Report (EEA) 2011
  - SOER (EEA) 2015
  - UN-GEO-5 (UNEP) 2012
- **Regional Policies, Urban**
  - CAP Rural development reporting (DG-AGRI & MS)
  - EU Territorial Spatial Perspective (Territorial Agenda) (MS) 2011
  - IUME Towards an Integrated Urban Monitoring in Europe (DG Regio, ESTAT, JRC, EPSON, MS)
- **Agriculture**
  - Agricultural land use change - agri-environment indicators (post IRENA) (DG-AGRI, ESTAT, EEA) end 2010
  - HNV (High Natural Value) farmland update (DG-ENV, EEA)
  - Biofuel Directive
  - Soil Strategy
- **Biodiversity**
  - Habitats and Birds Directive (MS, DG-ENV)
  - Ramsar Convention (wetlands) (MS)
  - CITES Convention (MS)
  - Biodiversity Action Plan (BAP) (DG ENV)
  - SEBI Indicators (EEA)
- **Water**
  - WFD River Basin Management Plans 2015 good ecological status and pressures from diffuse sources (MS – DG-ENV)
  - SOE report on water 2012 (EEA) (see also WISE 2010)
  - Water Accounts (annually) (EEA / UNSD)
  - Flood Directive risk assessment and mapping 2011/2015/2018
- **Forestry**
  - UNECE State of European Forests (2011)
  - European Forest Sector Outlook (2011)
  - MCPFE Forest Europe
  - FAO – FRA (2015) UNFF Conventions

Source: Jochum and Lacaze (2012)

LCLU information links to policies, reporting and assessment

- **Climate Change**
  - Clearinghouse on Adaptation (EEA, DG-Climate) 72
  - UNFCCC – LULUCF Land use, land-use change and forestry (MS - UNFCCC)
  - GCOS Essential Climate Variables (MS - WMO) annually
- **Air quality, transport, noise**
  - Effects of air pollution on human health
  - Ecosystem effects of air pollution:
  - Critical Loads assessments
  - Information on river/stream basins/catchments (e.g. contribution of atmospheric nitrogen deposition to water pollution)
  - Air pollutant emissions:
  - Forest cover (e.g. biogenic NMVOC emissions)
  - Agricultural land-use (e.g. ammonia emissions)
  - Road network in Europe (line source air pollutant emissions)
  - Agriculture and road network (among others) are covered by the Emission Inventory Guidebook, relevant chapter
  - Reporting to UNECE CLRTAP
- **Natural hazards and technological accidents**
  - Disaster prevention (e.g. Council Conclusion Nov 2009; EP resolution Sept 2010)
  - Seveso II Directive 96/82/EC (EC, 1996a) as amended by 2003/105/EC (EC, 2003a) on the prevention and mitigation of major industrial accidents.
  - The IPPC-Directive 96/61/EC (EC, 1996b; codified by Directive 2008/1/EC, EC, 2008) with the main objective focused on integrated permitting and accident prevention
  - Directive 85/337/EEC on Environmental Impact Assessment (EC, 1985; amended by 97/11/EC, EC, 1997; and 2003/35/EC, EC, 2003b)
  - Directive 2001/42/EC on Strategic Environmental Assessment (EC, 2001)
  - The European Spatial Development Perspective (EC, 1999)47

Source: Jochum and Lacaze (2012)

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DPSIR system
has been widely adopted as a framework for policy analysis

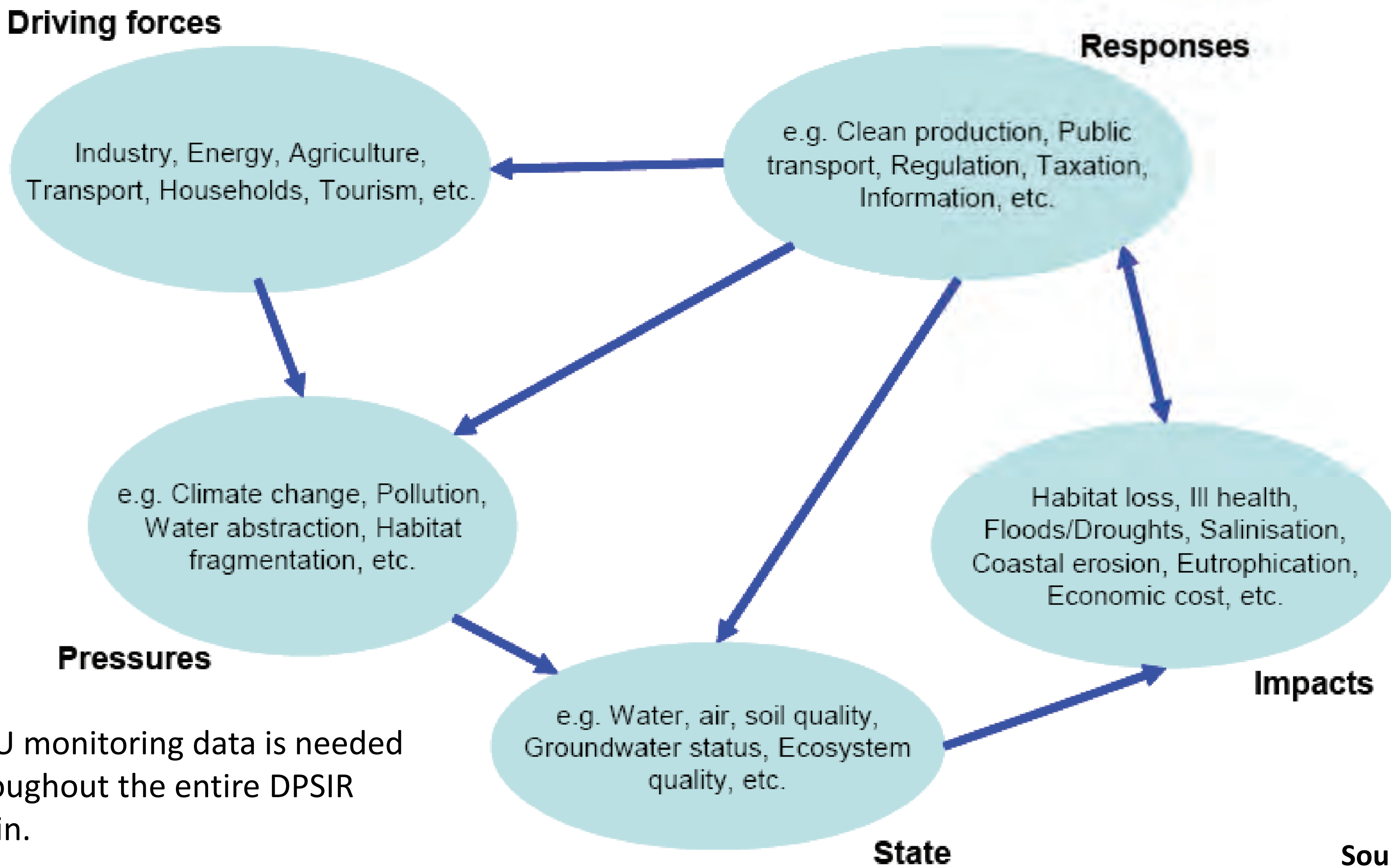
The need for LCLU monitoring

DPSIR for terrestrial environments

Driving Forces	Pressure	State	Impact	Responses
Climate change Globalisation Agricultural policy Technological advances Economic development	Land use Management practices Urbanisation Atmospheric emissions Species introductions	Habitat extent Habitat quality Species numbers Species distributions Soil erosion Soil pollution Meteorology Soil fertility Wildfire extent	Loss of amenity Loss of genetic resource Sedimentation	Habitat protection Species protection Land use planning Agricultural policy

Source: EC (2004)

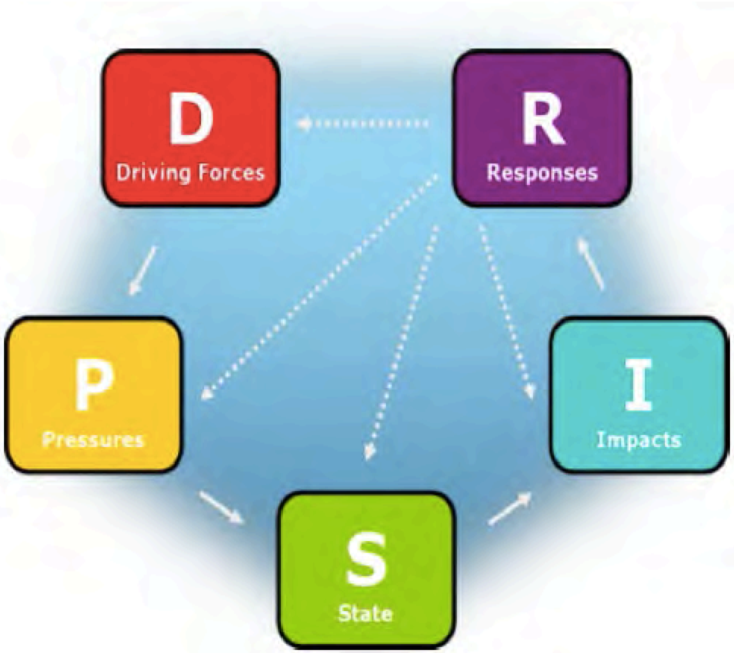
The DPSIR framework to report on environmental issues

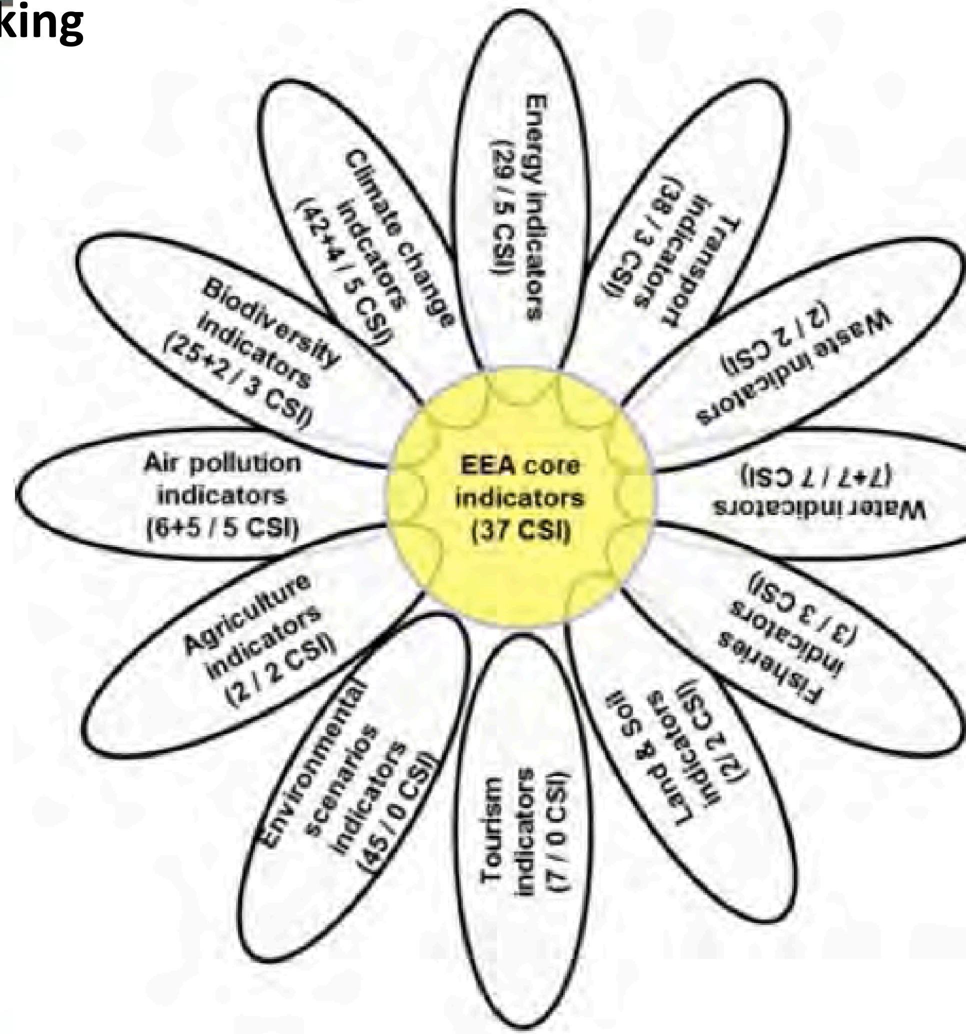


LCLU monitoring data is needed throughout the entire DPSIR chain.

Source: EEA

Indicators for evidence based policy making





Source: Dufourmont (2012)

Local changes have **global** impacts
(but global forces are now intensifying or attenuating local factors)

Change of economic opportunities

Population

National markets and policies

→

Food
Fiber
Forest
Water
Shelter

→

Croplands
Urban
Pastures
Forests

→

Energy (carbon)
Water
Fertilizer

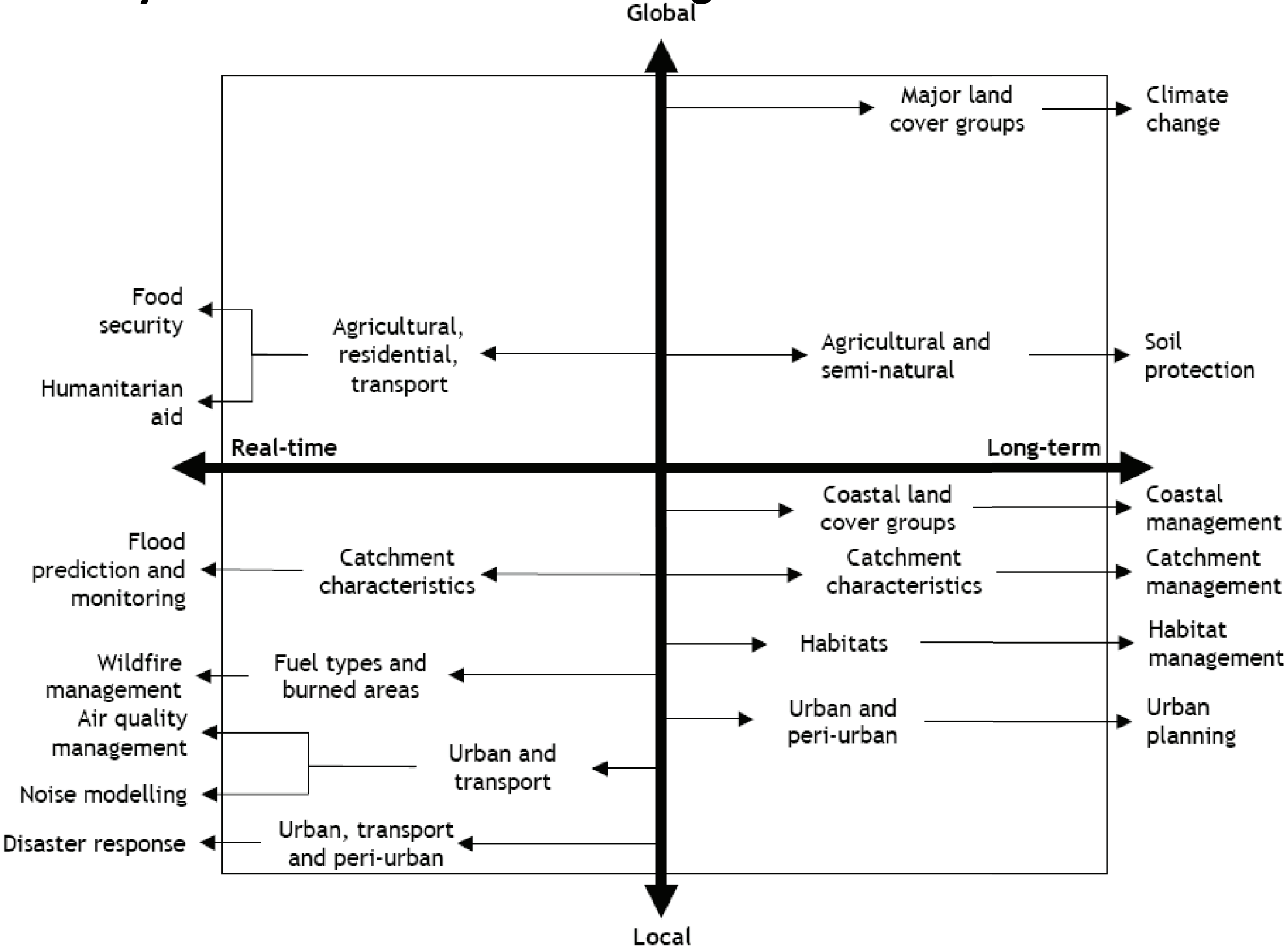
→

Capacity of ecosystems to:
- Sustain food production
- Maintain freshwater
- Maintain forest resources
- Regulate climate and air quality
- Ameliorate infectious diseases

We face the challenge of managing trade-offs between immediate human needs and maintaining the capacity of the biosphere to provide goods and services in the long term.

Source: Lambin et al. (2001); Foley et al (2005); http://socialclimate.wordpress.com

The diversity of needs for LCLU monitoring data



Source: EC (2004)

LCLU is recognised as one of the most important types of spatial data in two important European initiatives

Copernicus

The European Earth Observation Programme (Previously known as GMES - Global Monitoring for Environment and Security)

- COM (2004) 65 final – GMES: Establishing a GMES
- capacity by 2008 - (Action Plan (2004-2008))
- COM(2005) 565 final - GMES: From Concept to Reality
- COM(2008) 748 final - GMES: We care for a safer planet
- Regulation 911/2010 on GMES and its Initial Operations (GIO)
- COM(2011) 831 on the European Earth monitoring programme (GMES) and its operations (from 2014 onwards)
- Regulation 377/2014 establishing the Copernicus Programme and repealing Regulation (EU) No 911/2010

INSPIRE

Infrastructure for Spatial Information in the European Community

Directive 2007/2/EC

http://inspire.jrc.ec.europa.eu

ESA Web site **http://www.esa.int/Our_Activities/Observing_the_Earth/Copernicus**

EC Web site

http://www.copernicus.eu or http://ec.europa.eu/growth/sectors/space/copernicus/index_en.htm

Copernicus

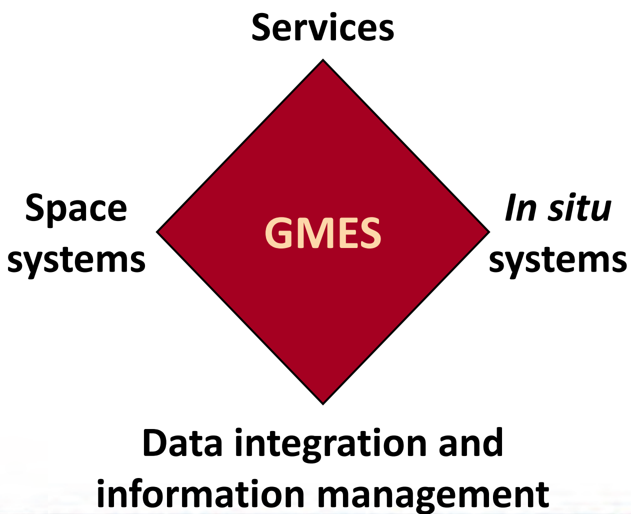
Copernicus is a initiative of the EU designed to establish a European capacity for the operational delivery and use of information in support of Environment and Security policies, and it is implemented together with ESA and Member States

It provides **autonomous and independent access** to information for policy-makers, particularly in relation to environment and security.

ESA implements the space component and the EC manages actions for identifying and developing services.

Copernicus will use, to the maximum extent possible, **existing capacities in Member States** or at European level.

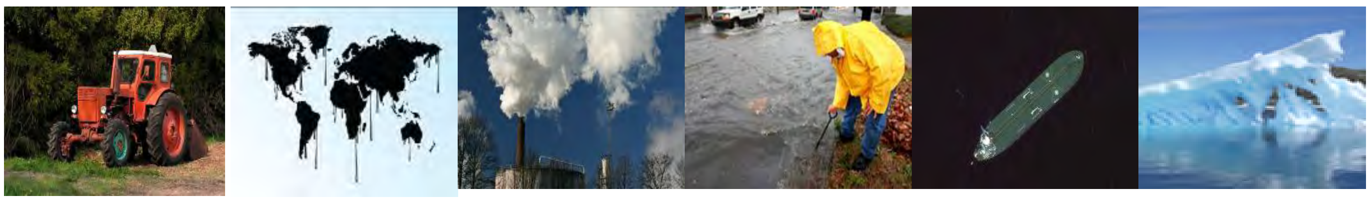
Copernicus is the European contribution to the Global Earth Observation System of Systems (**GEOSS**)
(in 2005 61 countries agreed on a 10-year GEOSS implementation plan).



USERS

Policy makers & Public & Private, commercial

← What is their need?



Farming | Oil Spill Tracking | Air quality | Flood | Surveillance | Climate Change

← Examples provided

Land | Marine | Atmosphere | Emergency | Security | Climate

← Information services

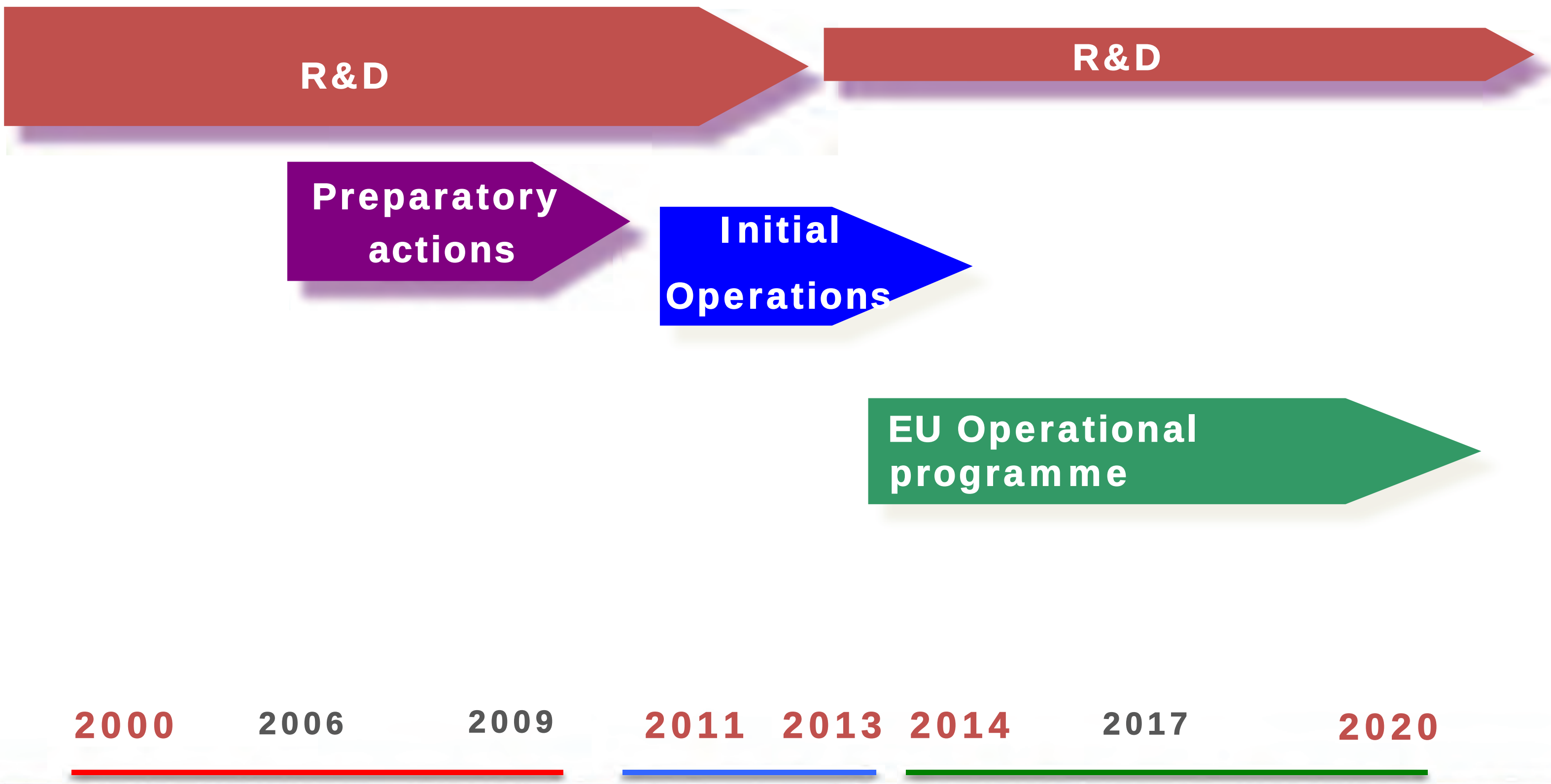
Space Infrastructure & In Situ Infrastructure

← Sustainable information

OBSERVATION

Source: EC

Copernicus evolution



Dedicated GMES financial appropriations until 2013 3 200 M€

- (Service and in situ components
  - EC 520 M€
  - ESA 240 M€)

- (Space component
  - ESA 1 650 M€
  - EC 780 M€)

2014-2020

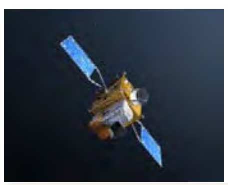
- EC (MFF) 3 786 M€
- EC (H2020) ?
- ESA 405 M€ + 1 600 M€ (+)

Data policy: full, free and open

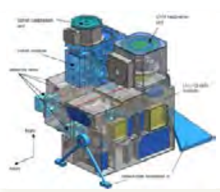
Sentinel 1 – SAR imaging
All weather, day/night applications, interferometry

Sentinel 2 – Multispectral imaging
Land applications: urban, forest, agriculture,..
Continuity of Landsat, SPOT

Sentinel 3 – Ocean and global land monitoring
Wide-swath ocean colour, vegetation, sea/land surface temperature, altimetry

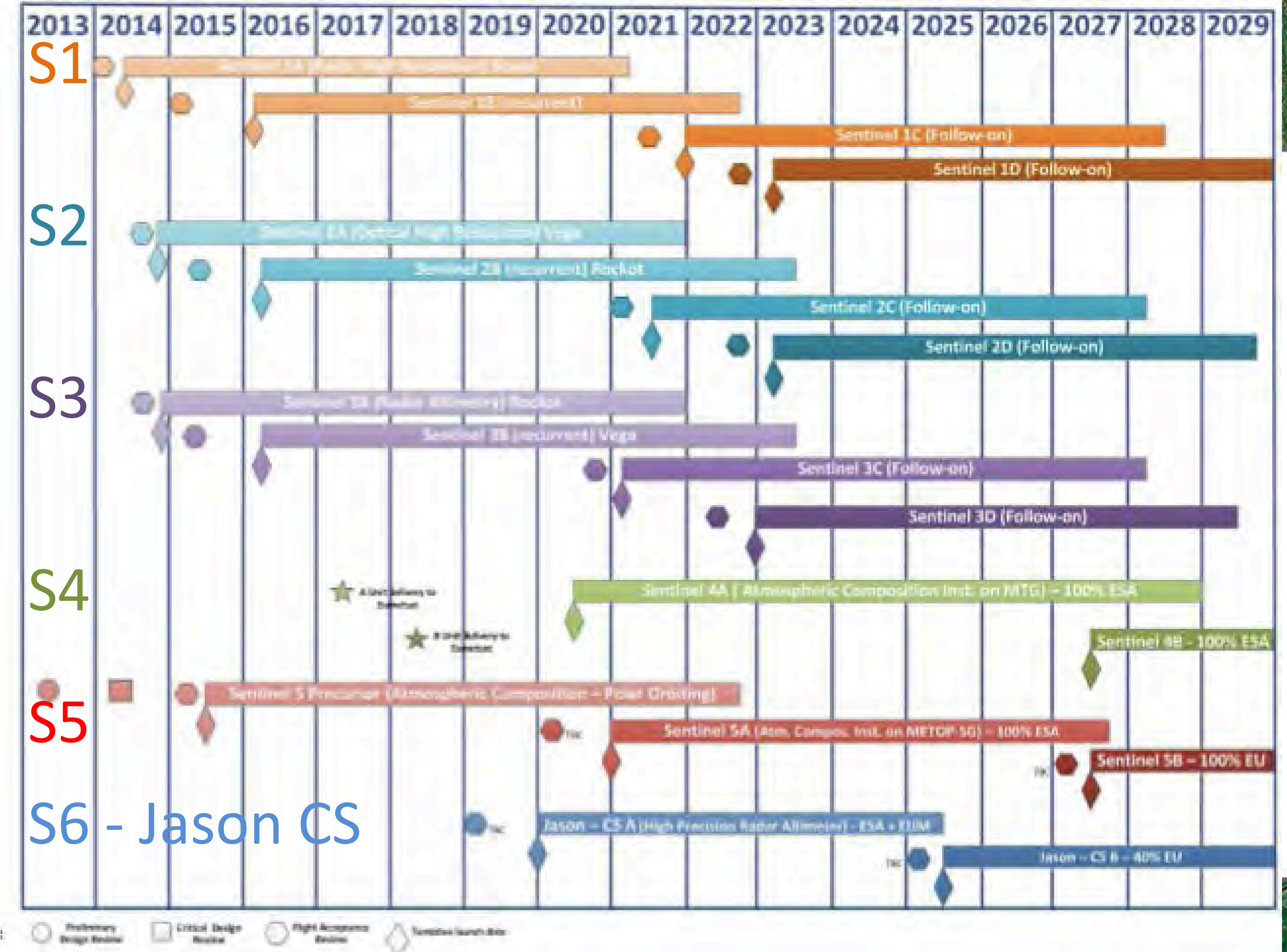


Sentinel 4 – Geostationary atmospheric
Atmospheric composition monitoring, trans-boundary pollution



Sentinel 5 and Precursor – Low-orbit atmospheric
Atmospheric composition monitoring

Sentinel 6 - JASON-CS


2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
S1
Sentinel 1C (Follow-on)
Sentinel 1D (Follow-on)
S2
Sentinel 2C (Follow-on)
Sentinel 2D (Follow-on)
S3
Sentinel 3C (Follow-on)
Sentinel 3D (Follow-on)
S4
Sentinel 4B - 100% ESA
S5
Sentinel 5B – 100% EU
S6 - Jason CS

INSPIRE

INSPIRE is a Directive proposed by the EC in July 2004 setting the legal framework for the establishment and operation of an **Infrastructure for Spatial Information in the European Community**.

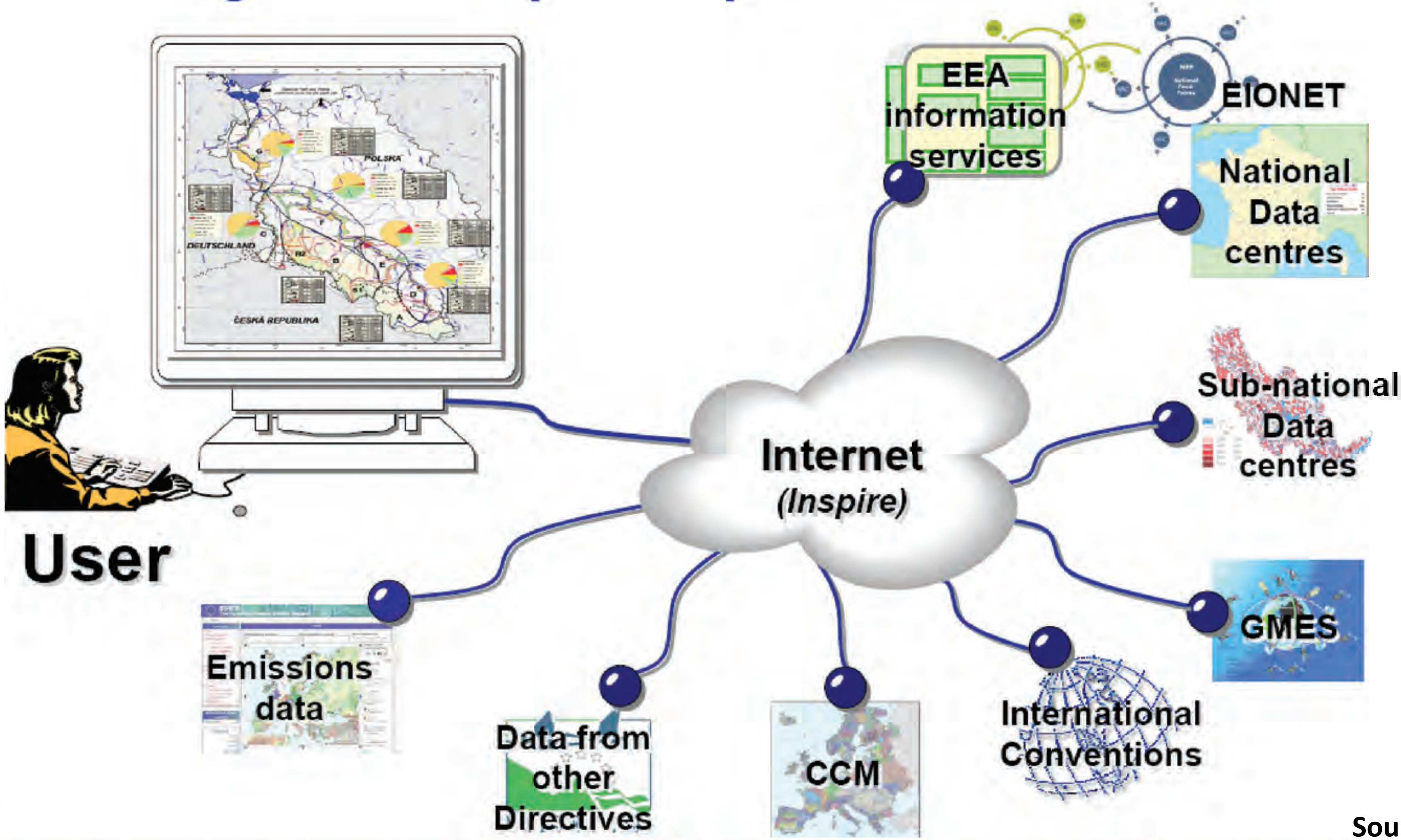
The purpose of INSPIRE is to **support** the formulation, implementation, monitoring activities and evaluation of **Community policies** and activities that may have a direct or indirect impact on the environment at various levels of public authority, European, national and local.

The **components** of INSPIRE infrastructures include: **metadata**; spatial **data** themes; spatial data services; network services and technologies; agreements on data and service sharing, **access** and use; coordination and monitoring mechanisms, processes and procedures.

INSPIRE should be based on the infrastructures for spatial information that are **created and maintained by the Member States**.

Member States will also ensure that the information is **shared between public bodies** and they would take steps to make geographical information more coherent.

Member States would make accessible their existing public sector geographical information over the **INTERNET**.


EEA information services
EIONET
National Data centres
Sub-national Data centres
Internet
(Inspire)
User
GMES
Emissions data
Data from other Directives
CCM
International Conventions

Source: EEA

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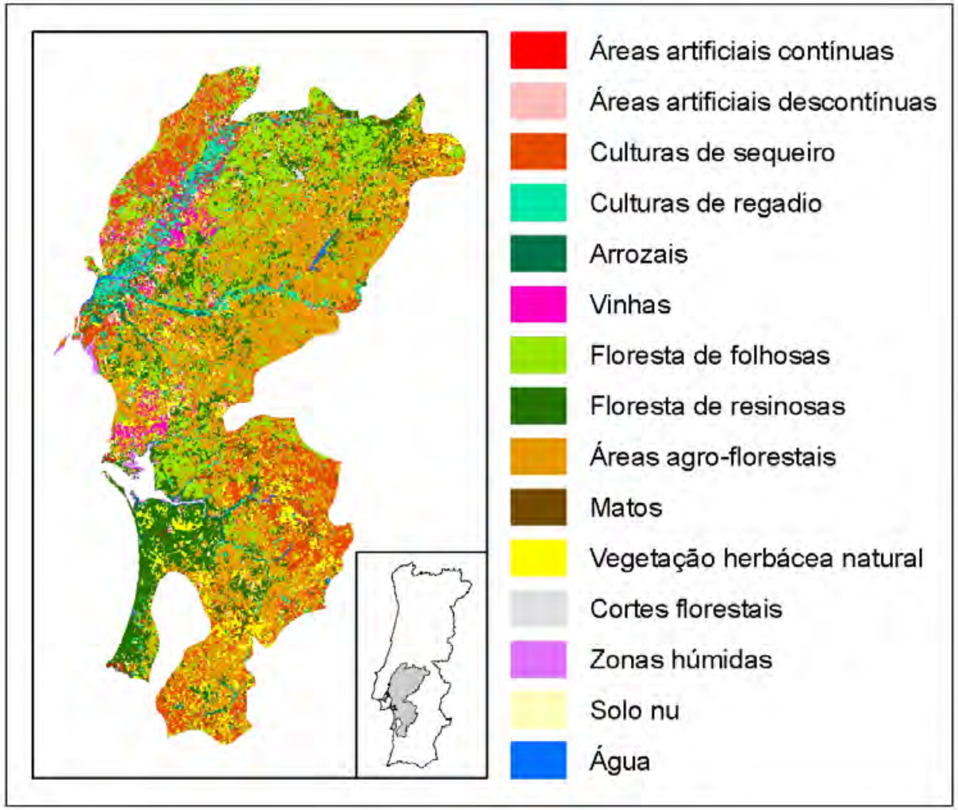
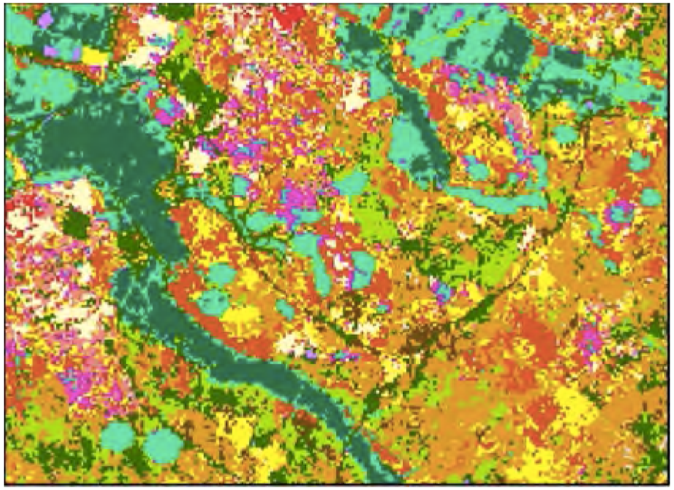
The traditional LCLU map

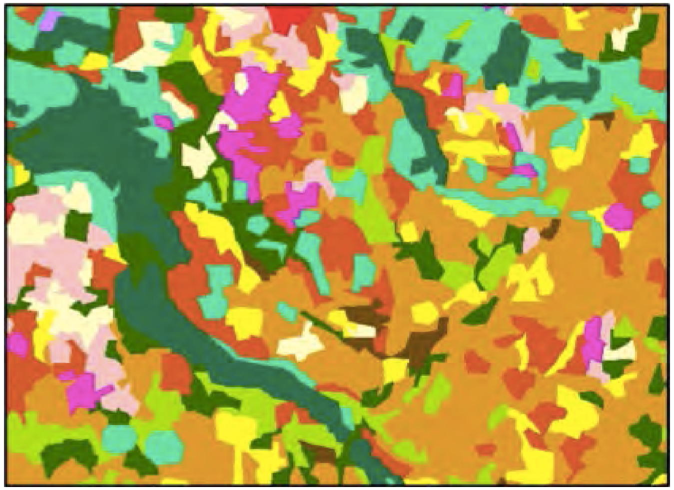
Spatial representation of a small number of classes that are mutually exclusive



Source: Boyd and Foody (2011)

The traditional LCLU map





Data model	**raster**	**vector**
Minimum Mapping Unit	**pixel**	**polygon**

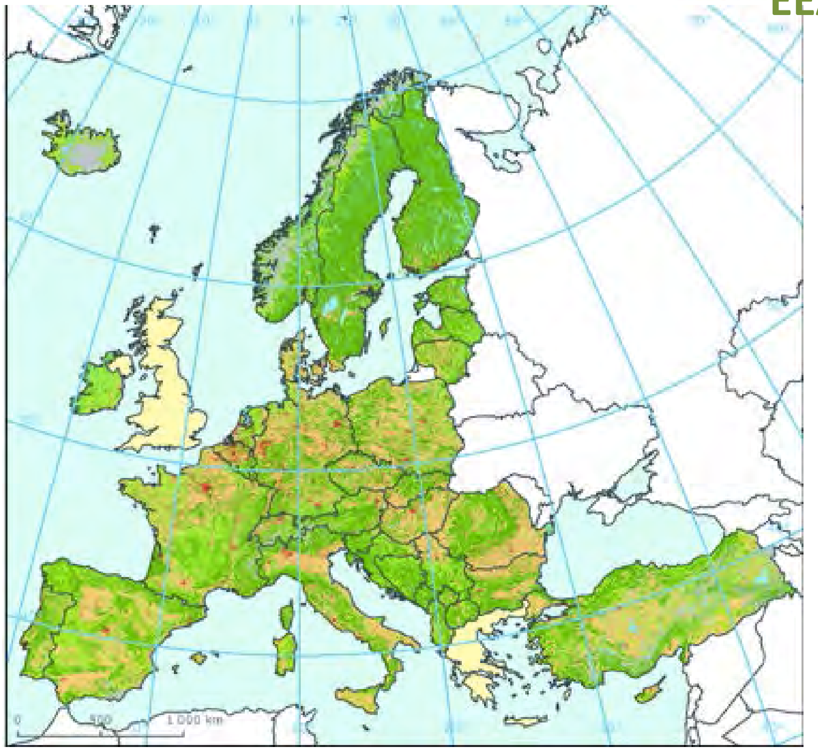
In each spatial unit (i.e. pixel, vector) there is one, and only one, class from a nomenclature that has a small number of classes.

Traditional LCLU maps in operational LCLU monitoring

National Land Cover Database

CORINE Land Cover

EEA



1992

2001, 2006, 2011

1990

2000, 2006, 2012

Traditional land cover map

In each spatial unit (i.e. pixel, vector) there is one, and only one, class from a nomenclature with a small number of classes.

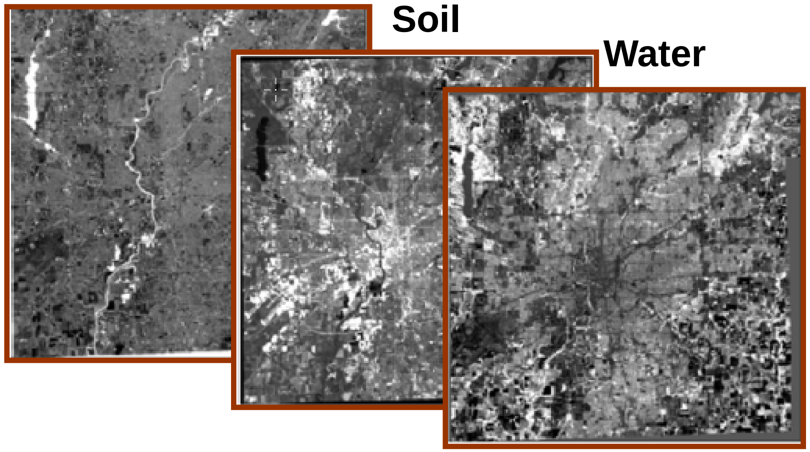
But….

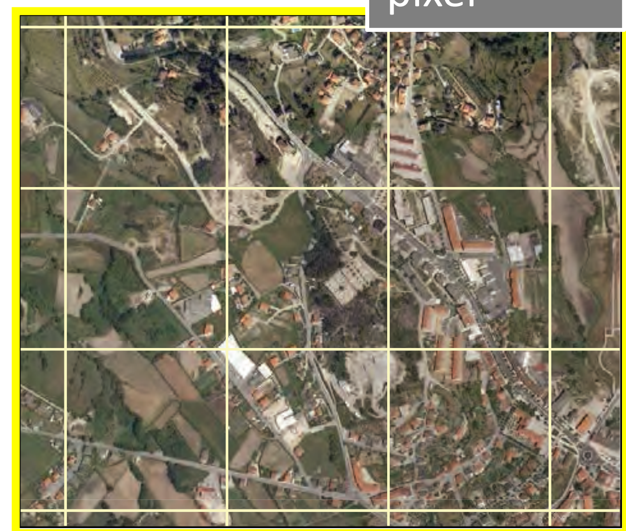
The real world is not hard but a continuum i.e. there are no crisp spatial borders between classes (Rocchini, D., e C. Ricotta, 2007)

Each pixel can have more than one class

Mixed pixel

Gradient maps **Continuum maps** **Fraction maps**





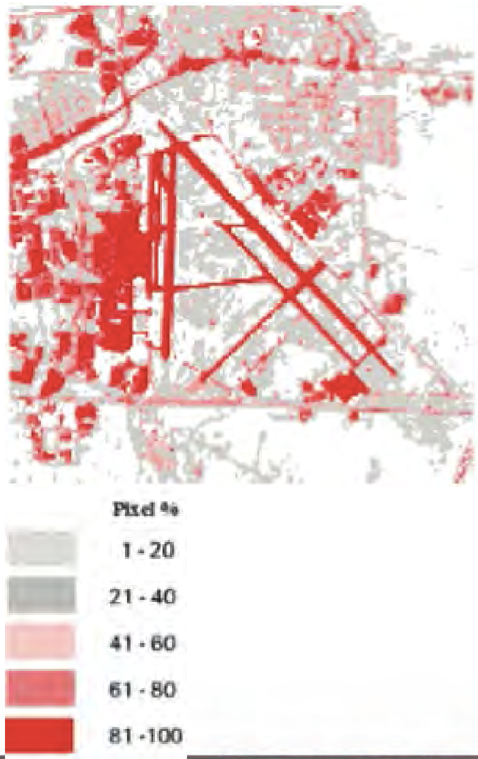
Representation of the abundance of a small number of classes (that usually represent land cover elements)

National Land Cover Database

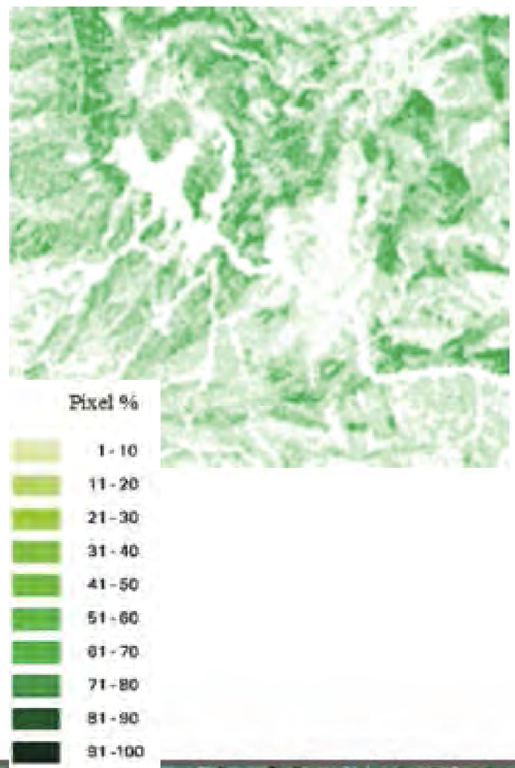
1992 2001, 2006, 2011

Pixel - 30 m

% urban imperviousness



% tree canopy



CORINE Land Cover

EEA

1990 2000, 2006, 2012

Pixel - 20 m

Copernicus

% soil sealing
2006 and 2009

2012
% soil sealing
% forest
% grassland
% water
% wetland

1972

A Land Use and Land Cover Classification System for Use with Remote Sensor Data

By JAMES R. ANDERSON, ERNEST E. HARDY, JOHN T. ROACH, *and* RICHARD E. WITMER

GEOLOGICAL SURVEY PROFESSIONAL PAPER 964

A revision of the land use classification system as presented in U.S. Geological Survey Circular 671

Anderson et al. (1976)

1985

EUROPE ENVIRONMENT

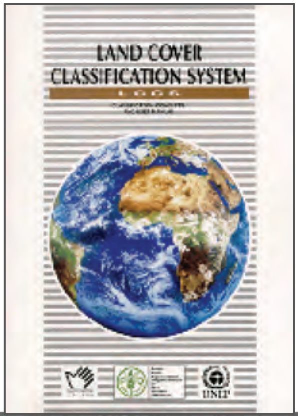
OUR JOINT FUTURE

DG XI FOR THE QUALITY OF LIFE

CORINE land cover

Bossard et al. (2000)

EEA



2000

Land Cover Classification System (LCCS) is an universal system

LCCS - instead of using pre-defined classes, it uses universally valid pre-defined set of independent diagnostic attributes, or classifiers.

Any land cover class, regardless of its type and geographic location, can be identified by a pre-defined set of classifiers.

LCCS is:

- Independent of map scale;
- Independent of data source and data collection methodology;
- Independent of geographic location;
- Independent of application.

Source: Di Gregorio (2005)

First level	Second level	Third level
PRIMARILY VEGETATED	TERRESTRIAL	MANAGED TERRESTRIAL AREAS
		NATURAL and SEMI-NATURAL TERRESTRIAL VEGETATION
	AQUATIC or REGULARLY FLOODED	CULTIVATED AQUATIC AREAS
		NATURAL and SEMI-NATURAL AQUATIC VEGETATION
PRIMARILY NON-VEGETATED	TERRESTRIAL	ARTIFICIAL SURFACES
		BARE LAND
	AQUATIC or REGULARLY FLOODED	ARTIFICIAL WATER BODIES
		NATURAL WATER BODIES, SNOW and ICE

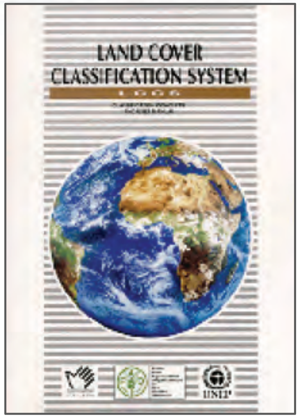
LCCS dichotomous classification phase.

Fonte: Di Gregorio (2005)

	Classifiers			
4	Life form of main layer (e.g. woody, herbaceous)	Vegetation cover of main layer	Vegetation height	Spatial distribution (macropattern)
5	Leaf type (e.g. broadleved, needleleaved, aphyllous)		Leaf phenology (e.g. evergreen, deciduous, mixed)	
6	Vertical stratification second/third layer	Vegetation cover second/third layer	Vegetation height second/third layer	

Set of classifiers and their hierarchical arrangement corresponding to the dichotomous class Natural and Semi-Natural Terrestrial Vegetation.

Fonte: Di Gregorio (2005)



2000

2008

LCCS
Versão 3

**Land
Cover
Macro
Language**

2012

ISO 19144-2:2012

The main advantage of LCML is that a **UML** (Unified Modelling Language) diagram, i.e. a **visual representation**, is easier to read and understand in non-technical contexts rather than the mathematical formalisation used for LCCS.

The UML concept model is converted into a computer **object-oriented format**, i.e. XML (Extensible Markup Language)

ISO 19144-2:2012 specifies a Land Cover Meta Language (LCML) expressed as a UML metamodel that allows different land cover classification systems to be described based on the physiognomic aspects.

Source: http://www.glcn.org/ont_2_en.jsp

Directive 2007/2/EC

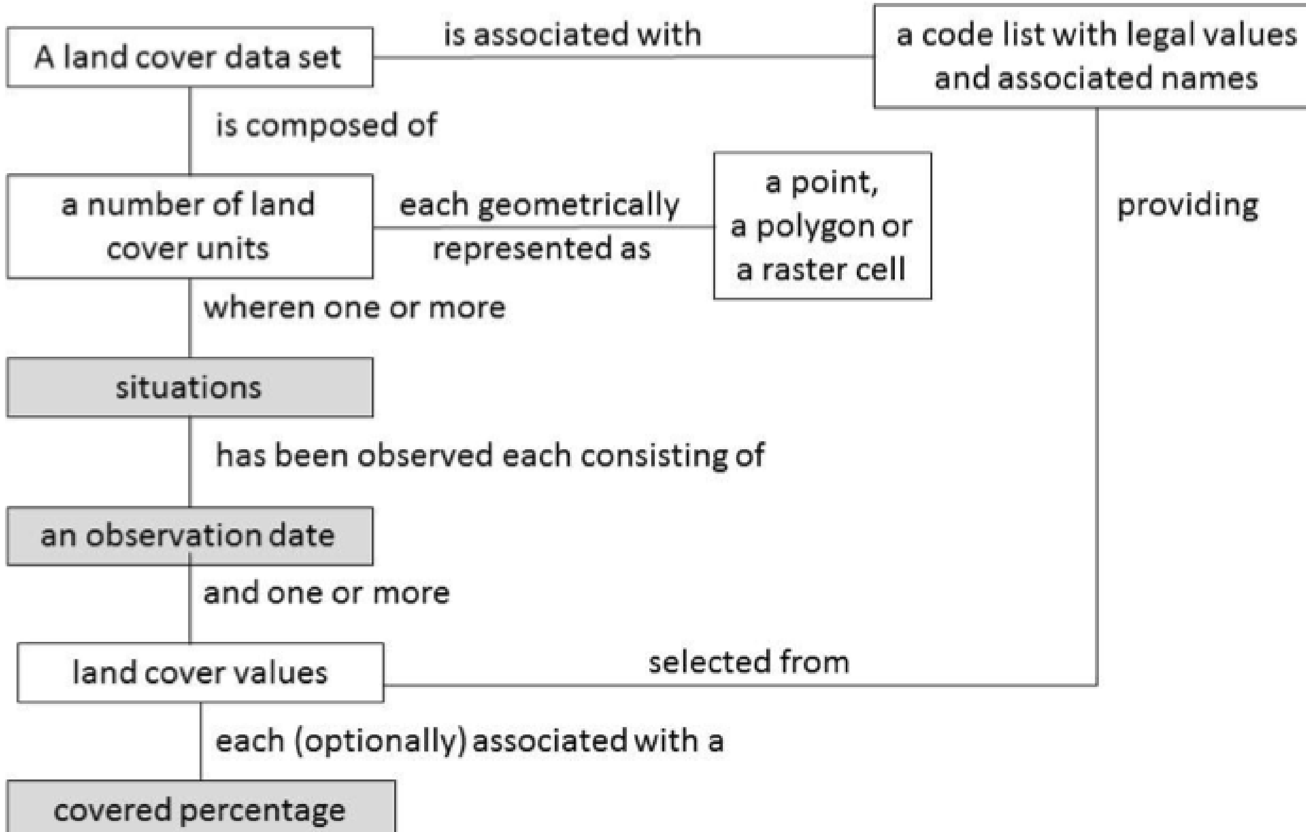
INSPIRE
Infrastructure for Spatial Information in Europe

INSPIRE
Infrastructure for Spatial Information in Europe

D2.8.II.2 Data Specification on Land cover – Draft Technical Guidelines

Title	D2.8.II.2 INSPIRE Data Specification on *Land* cover – Draft Technical Guidelines
Creator	INSPIRE Thematic Working Group *Land cover*
Date	2013-02-04
Subject	INSPIRE Data Specification for the spatial data theme *Land cover*
Publisher	INSPIRE Thematic Working Group *Land cover*
Type	Text
Description	This document describes the INSPIRE Data Specification for the spatial data theme *Land* cover This version (version 3, release candidate 3) reflects the content of the draft amendment to Commission Regulation (EU) No 1089/2010 for the Annex II+III spatial data themes as submitted to the INSPIRE Committee.
Contributor	Members of the INSPIRE Thematic Working Group *Land cover*
Format	Portable Document Format (pdf)
Source	
Rights	Public
Identifier	D2.8.II.2_v3.0rc3
Language	En
Relation	Directive 2007/2/EC of the European Parliament and of the Council of 14 March 2007 establishing an Infrastructure for Spatial Information in the European Community (INSPIRE)
Coverage	Project duration

Feb. 2013



Conceptual model for land cover

Object oriented data model

INPIRE Pure Land Cover Components (PLCP)

Data Specification on Land Cover - Draft Technical Guidelines

Code No.	Component Name	Legend Color
001	Artificial constructions	
002	Consolidated bare surface	
003	Unconsolidated bare surface	
004	Arable land	
005	Permanent woody and shrubby crops	
006	Coniferous forest trees	
007	Broadleaved forest trees	
008	Shrubs	
009	Herbaceous plants	
010	Lichens and mosses	
011	Wetlands and marshes	
012	Organic deposits (Peatland)	
013	Chemical deposits	
014	Intertidal flats	
015	Fresh water course	
016	Fresh water bodies	
017	Salt or brackish water	
018	Permanent snow and ice	

Summary

1 Setting the scene

2 The need for LCLU monitoring data

- LCLU: a cross-cutting environmental variable
- LCLU monitoring and environmental legislation
- Relation between two European initiatives (Copernicus and INSPIRE) and LCLU monitoring
- Hard and soft LCLU maps
- The Land Cover Classification System

3 From data to information: some important advances in LCLU monitoring

- Two different approaches for LCLU monitoring
- Spectral and class change detection
- Image classification for LCLU mapping

4 LCLU monitoring operational programs

- At country level (NLCD from USA)
- At European level (Land monitoring service within Copernicus)
- At Global level (GLOBCOVER)

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LCLU monitoring

It is related to **characterisation over time** and the moments in time usually refer to **different years.**

Most important LCLU monitoring programs also include the mapping of LCLU changes through the years, i.e. change identification and characterisation. This means that those programs **include not only LCLU but also LCLUCC mapping**.

LCLU monitoring

Change detection techniques can also be applied to images for the **same year** but from different seasons. In this case one is not doing LULCC mapping but capturing **different conditions** of the same LCLU classes instead (i.e. forest fires, phenology of agriculture crops).

One should differentiate:

- changes within classes - **modification**
- changes between classes - **conversion** (Giri, 2012).

LCLU monitoring

There are two types of land cover monitoring:

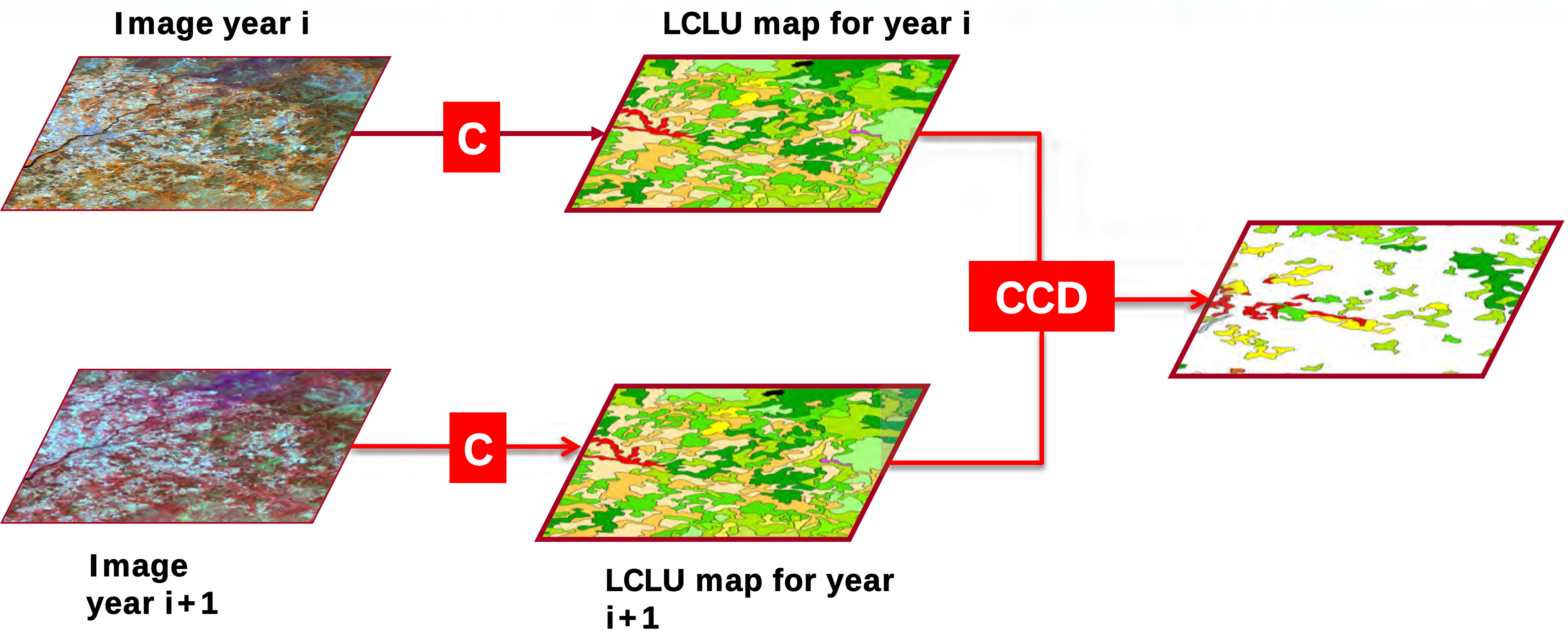
- LCLU maps for different years are **independently** produced (e.g. GLOBCOVER)
- LCLU maps are produced in a **temporarily consistent** manner (e.g. CORINE LC and current NLCD)

LCLU monitoring by independent LCLU map production

LCLU maps for different years are produced through the **independent** application of **image classification** techniques to the images of the different years.

Change detection and/or characterisation (i.e. LCLUC) is done through **post-classification** map comparison.

LCLU monitoring by independent LCLU map production



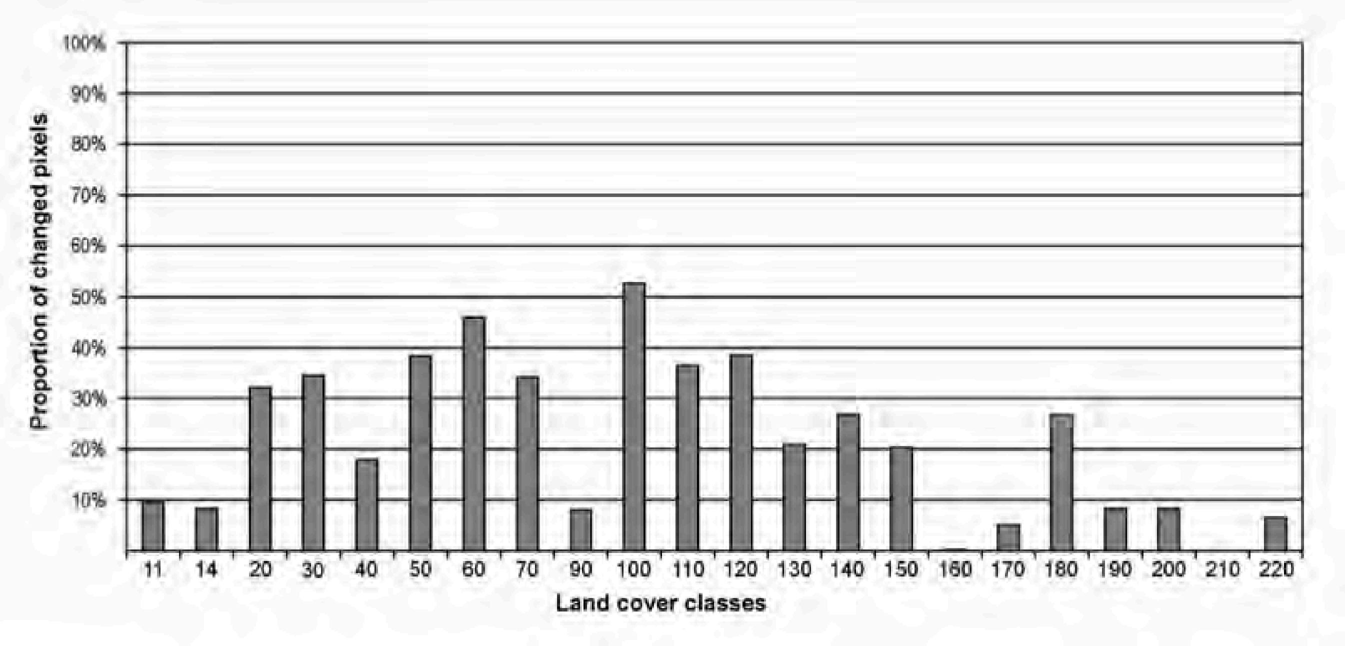
LCLUC most likely does not indicate real changes but instable classifications instead

CCD Class Change Detection **C** Image classification

GLOBCOVER 2005 and 2009

"Pixels that are differently classified in the GlobCover 2005 and 2009 land cover maps are too numerous to be representative only for land cover changes.

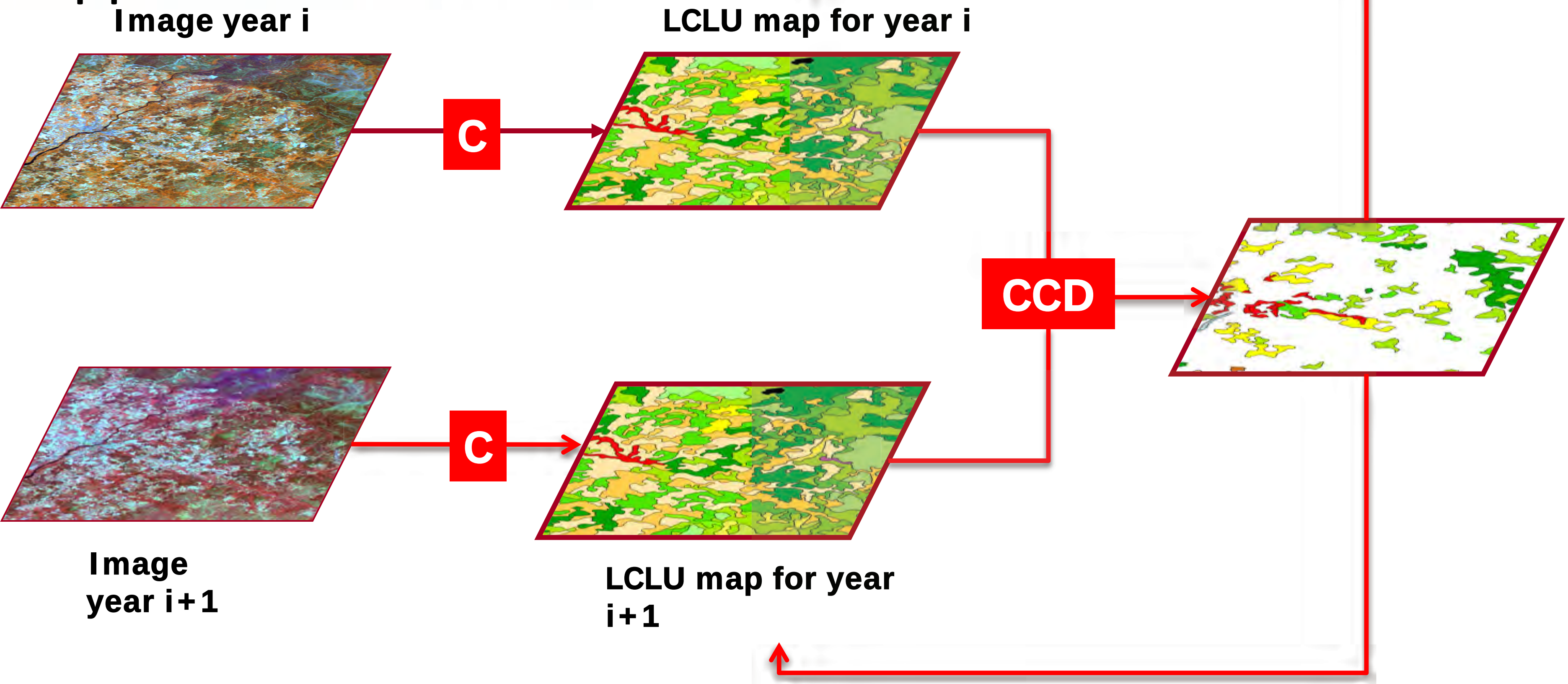
They should rather be interpreted like classification instabilities."



There is a temporal inconsistency and therefore land cover change studies are not possible

Source: Bontemps et al. (2011)

LCLU monitoring by independent LCLU map production



LCLUC map is iteratively used to make the LCLU maps for different years comparable

CCD Class Change Detection

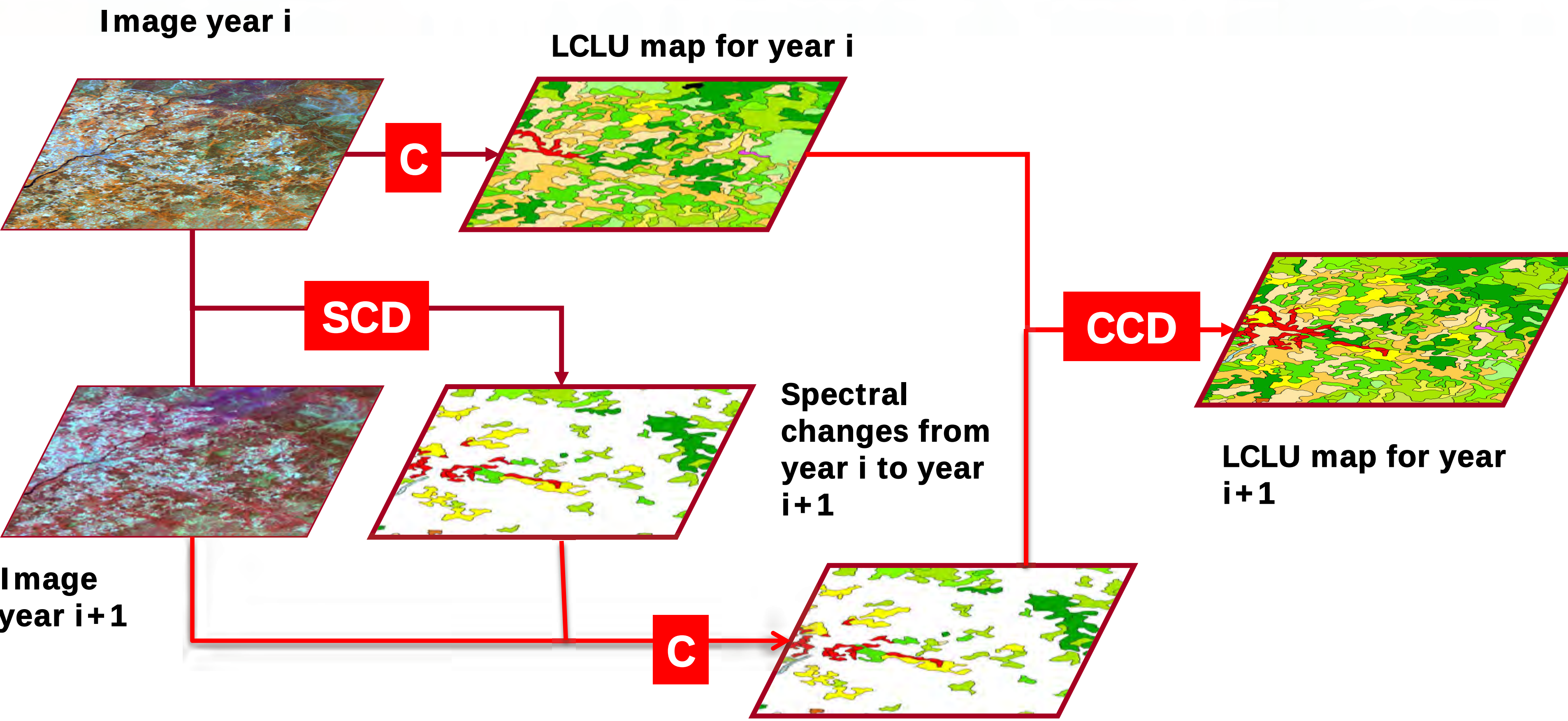
C Image classification

LCLU monitoring by a temporally consistent manner

A first LCLU is produced for a given year.

The production of a LCLU map for a following year is produced based on **spectral change detection** techniques followed by **image classification**

LCLU monitoring by a temporally consistent manner



SCD Spectral Change Detection **CCD** Class Change Detection **C** Image classification

Change detection

Spectral change detection

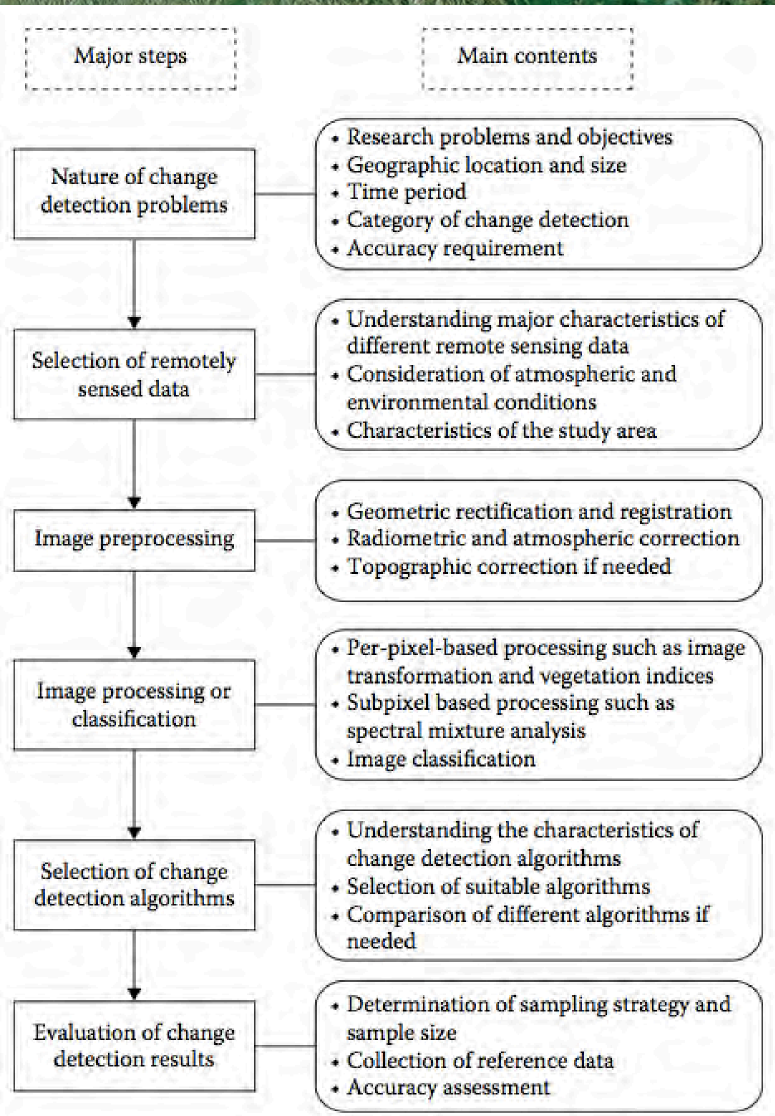
Change detection techniques are applied to identify changes on the spectral characteristics of the spatial units (e.g. pixels). It also includes techniques that take into account the spatial arrangement of the pixels (i.e. contextual information)

Class change detection

Change detection consists on a post-classification comparison (i.e. GIS overlay)

This is a very simple way to approach change detection. There are other approaches much more comprehensive.

A proposal for a change detection procedure



Source: Lu et al., 2011

Although a large number of change detection applications have been implemented and different change detection techniques have been tested, the question of which method is best suited for a specific study area remains unanswered. No single method is suitable for all cases. The method selected depends on an analyst's knowledge of the change detection methods and skills in handling remote sensing data, the image data used, and characteristics of the study areas. Lu et al. (2011)

Examples of simple methods for spectral change detection

Change vector analysis

Principal Component Analysis

Image differencing (bands, NDVI)

There is a 2013 IEEE special issue on multitemporal remote sensing with five paper on change detection
IEEE Transactions on Geoscience and Remote Sensing, (Volume:51 , Issue: 4) – Editors: F. Bovolo, L. Bruzzone and R. King.

NDVI image differencing

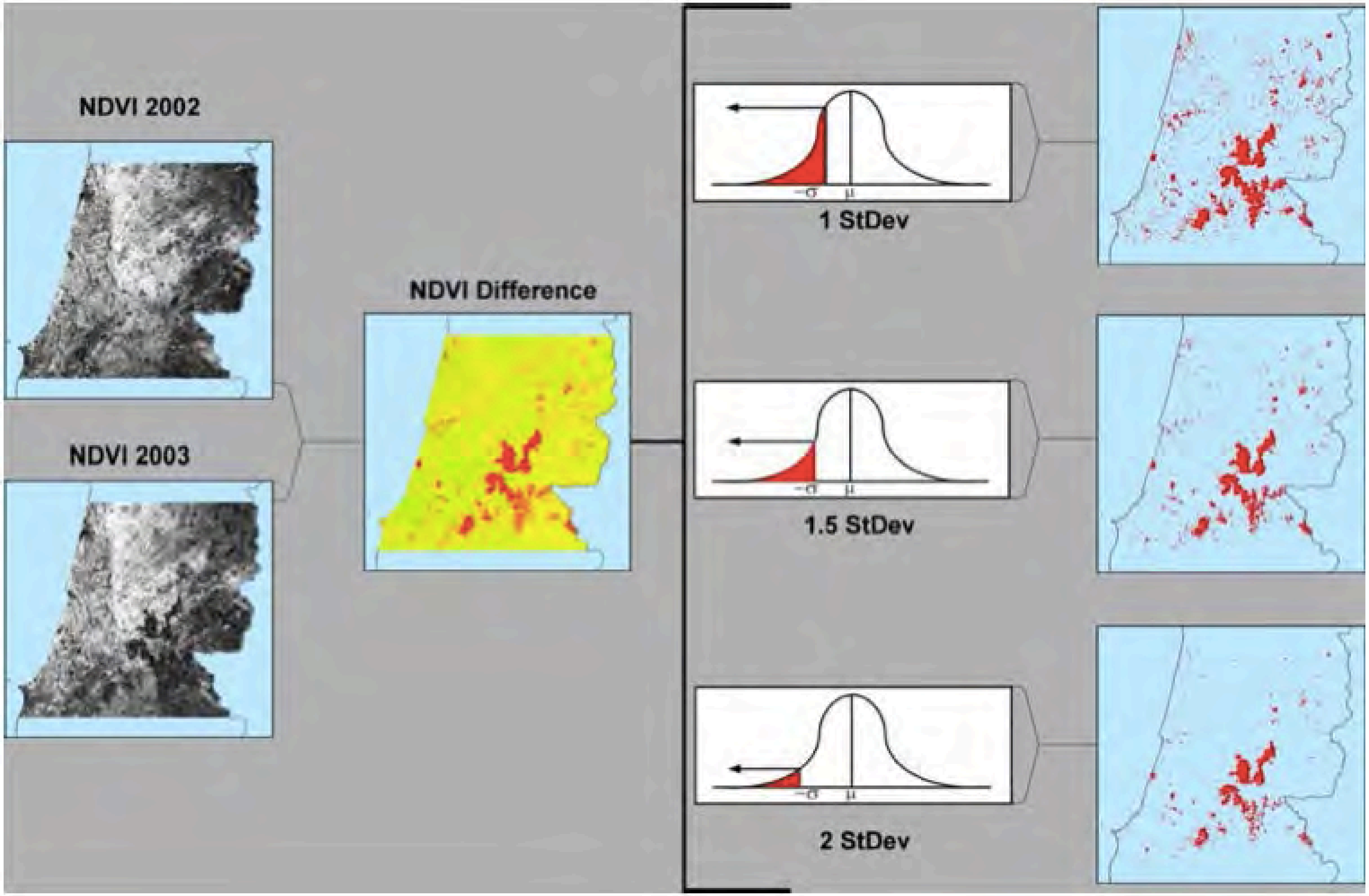


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Image classification for LCLU mapping

1 An integrated approach for LCLU mapping

2 Most common problems in image classification and how to solve them

e.g. mixed pixel problem, lack of normality of the training data, Hughes phenomenon

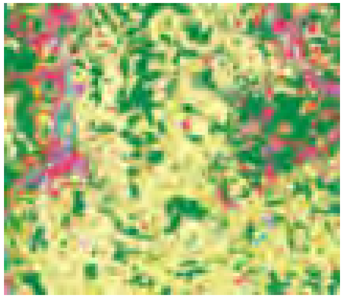
3 Most important advances in satellite image classification

e.g. from pixel to object, from hard to soft classifiers,
from parametric to non-parametric classifiers

LCLU information extraction from satellite images

Map of categorical variables

Map of thematic classes



Land cover maps

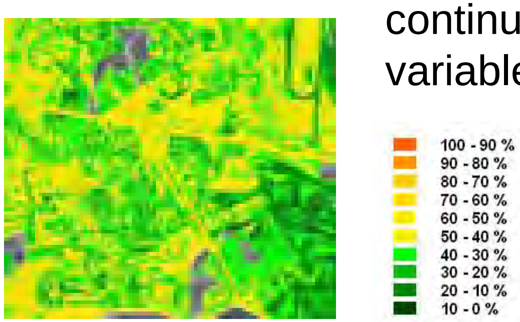
Burned area maps

Flooded maps

Agriculture maps

Forest maps

Map of continuous variables



Leaf area index

Biomass

Tree volume

Thematic remote sensing

Image classification

Quantitative remote sensing

Modelling

The traditional approach for LCLU mapping

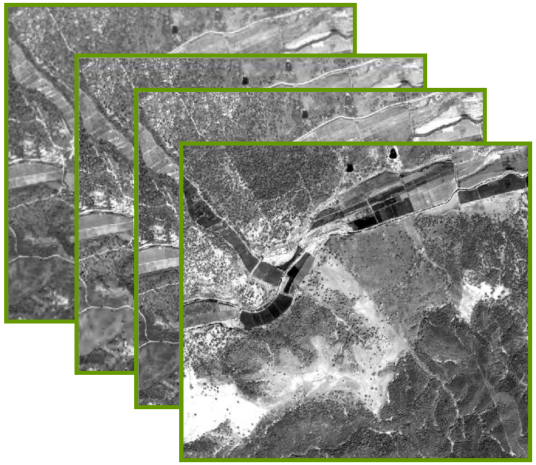
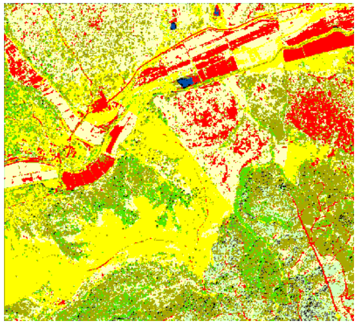


Image classification
at pixel level



Map of categorical classes

For many years the research emphasis has been on the classification step itself.

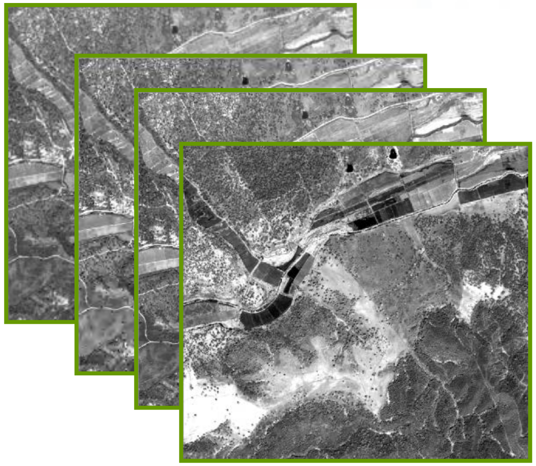
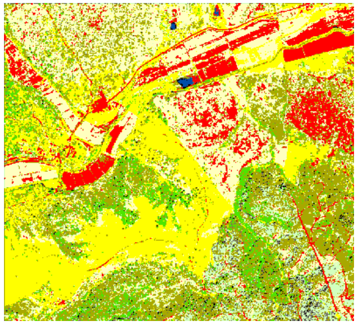


Image classification at pixel level



Map of categorical classes

Does it satisfy the user needs?

Recent research

- New classification algorithms
- A new spatial unit of analysis
- Spatial analysis for map generalisation

→ Redefine the approach for thematic information extraction

Recent advances in satellite image classification

1. Development of **components of the classification algorithm**, including training, learning and approaches to class separation

e.g. artificial neural networks, decision trees

2. Development of **new systems-level approaches** that augment the underlying classifier algorithms

e.g. fuzzy or similar approaches that soften the results of a hard classifier, multiclassifier systems that integrate the outputs of several classification algorithms

3. Exploitation of **multiple** types of data or ancillary information (numerical and categorical) in the classification process

e.g. use of structural or spatial context information from the imagery, use of multitemporal data, use of multisource data, use of ancillary geographical knowledge in the overall classification system

Source: Foody et al. (2009) and Wilkinson (2005)

Thematic information extraction from satellite images

1 Definition of the mapping approach *

2 Geographical stratification

3 Image segmentation

4 Feature identification and selection *

5 Classification *

6 Ancillary data integration

7 Post-classification processing

8 Accuracy assessment *

* mandatory

Thematic information extraction from satellite images

1 **Definition of the mapping approach** *

2 Geographical stratification

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* mandatory

1. Definition of the mapping approach

The mapping approach has to take into account, e.g.

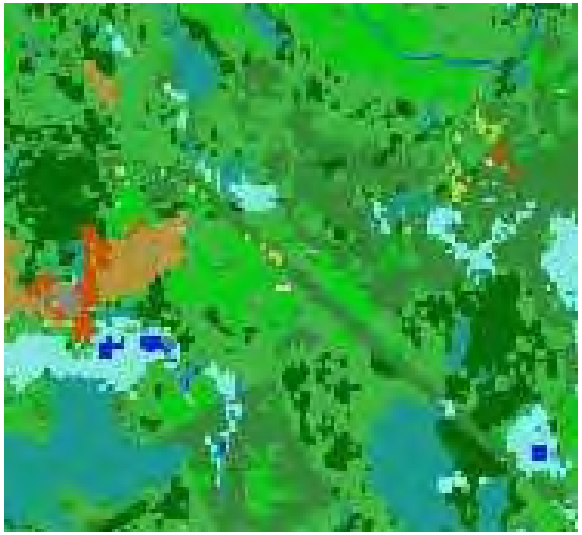
Characteristics of the satellite data to be used	→	Definition of the spatial unit of analysis
Technical specifications of the final map (e.g. MMU)	→	Definition of the spatial unit of analysis
Characteristics of the geographical area to be mapped	→	Decision on stratifying the study area
Availability of ancillary data	→	Decision on the use of ancillary data

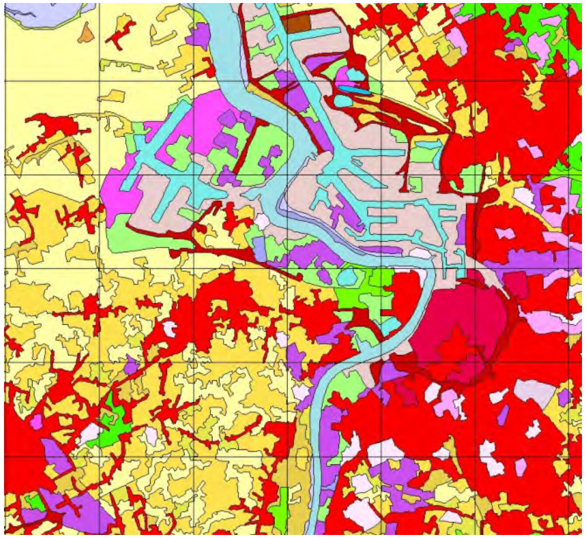
MMU = Minimum Mapping Unit

1. Definition of the mapping approach

Minimum Mapping Unit (MMU)

The MMU is the smallest area that is represented in a map





In raster maps the MMU usually is the pixel

e.g. in the NLCD 2001 (USA) the MMU is 30x30 m pixel

In vector maps the MMU is the smallest object/polygon that is represented in the map

e.g. in the CORINE Land Cover (CLC) maps (from EEA) the MMU is 25 ha

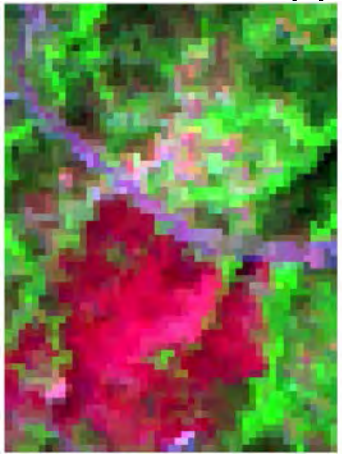
NLCD = National Land Cover Database

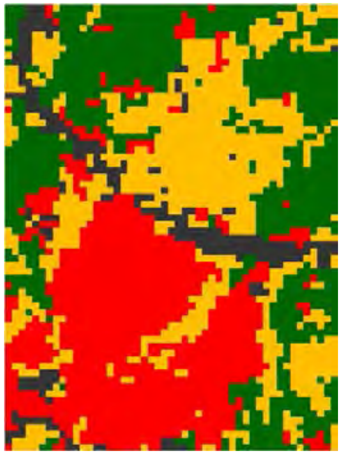
EEA – European Environment Agency

1. Definition of the mapping approach

Spatial unit of analysis This is the unit to which the classification algorithms will be applied

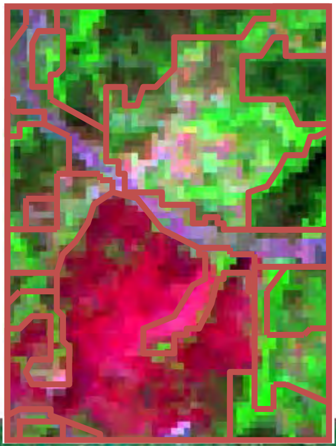
Image pixel

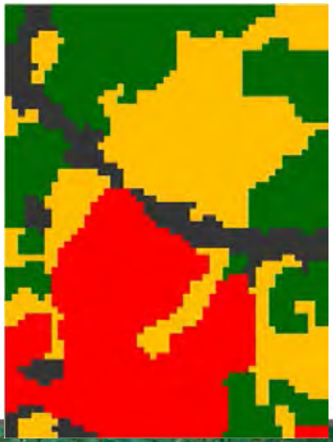




Per pixel or sub-pixel classification

Object





Object oriented image classification

1. Definition of the mapping approach

The selection of the **spatial unit of analysis** depends on:

- Spatial resolution of the satellite image
- Type of thematic information we want to extract, e.g. land cover, land use
- Format of the map we want to produce, i.e. vector or raster
- Minimum Mapping Unit of the final map
- Post-processing tasks that we are planning to apply

1. Definition of the mapping approach

The steps required to information extraction depend on the defined mapping approach:

Map format = raster

MMU = pixel size of input satellite data

Feature selection > Image classification > accuracy assessment

MMU > pixel size of input satellite data

Feature selection > Image classification > post-processing > accuracy assessment

↕ **upscaling**

Map format = vector

Spatial unit of analysis = image pixel

Feature selection > Image classification > post-processing > accuracy assessment

↕ **Generalisation + Raster to vector conversion**

Spatial unit of analysis = object

Image segmentation > Feature selection > Image classification > post-processing > accuracy assessment

↕ **Generate the objects** (Image segmentation)

↕ **Generalisation** (post-processing)

Thematic information extraction from satellite images

1 Definition of the mapping approach *

2 **Geographical stratification**

3 Image segmentation

4 Feature identification and selection *

5 Classification *

6 Ancillary data integration

7 Post-classification processing

8 Accuracy assessment *

* mandatory

2. Geographical stratification

Geographical stratification – the study area is divided into smaller areas (strata) so that each strata can be processed independently.

Five general concepts are useful in geographical stratification:

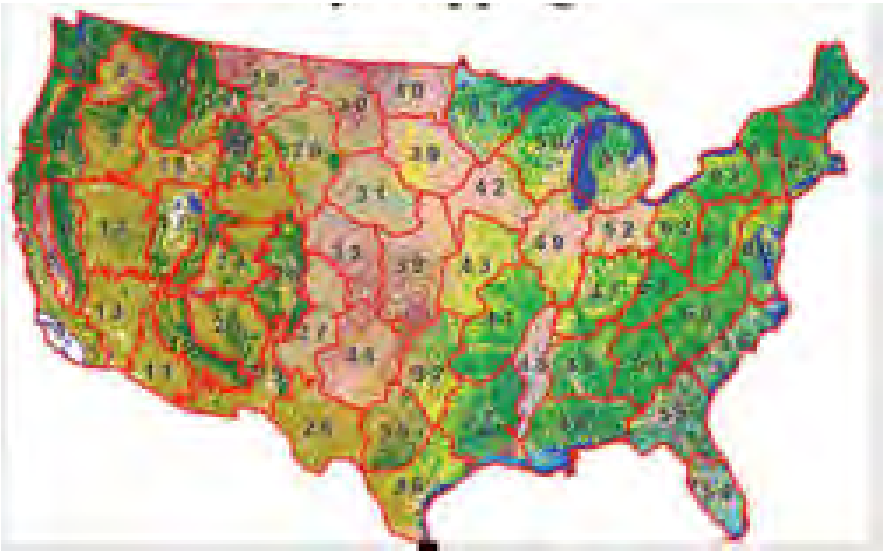
- economics of size,
- type of physiography,
- potential land cover distribution,
- potential spectral uniformity,
- edge-matching issues.

Data that can be used for geographical stratification

- Slope
- Aspect
- Elevation
- Existent land cover/use maps
- Climate data
- Vegetation maps

2. Geographical stratification

Geographical stratification used on the production of the US National Land Cover Database (NLCD) - 2001



Input data

- 83 Level III ecoregions developed by Omernik
- NLCD 1992
- AVHRR normalized greenness maps

Source: Homer et al. (2004)

AVHRR - Advanced Very High Resolution Radiometer

Thematic information extraction from satellite images

1 Definition of the mapping approach *

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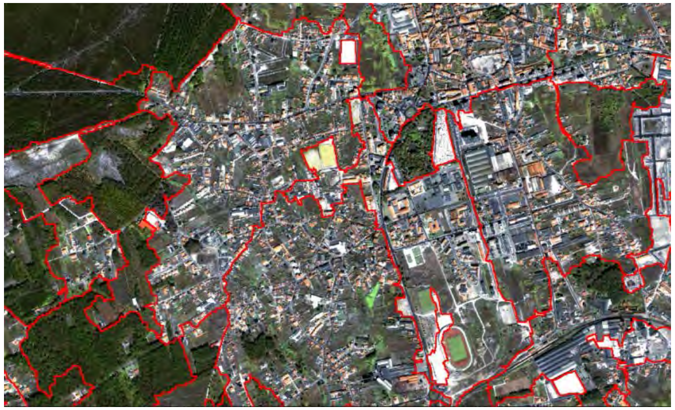
* mandatory

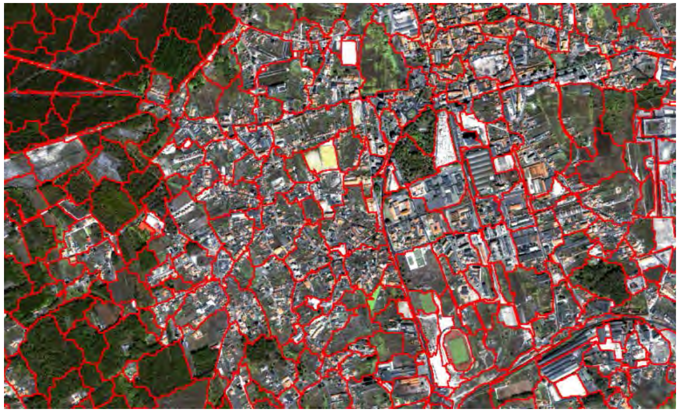
3. Image segmentation

This step is only required if the spatial unit of analysis is the **object**.

Segmentation is the division of an image into spatially continuous, disjoint and homogeneous regions, i.e. the objects.

Segmentation of an image into a given number of regions is a problem with a large number of possible solutions.

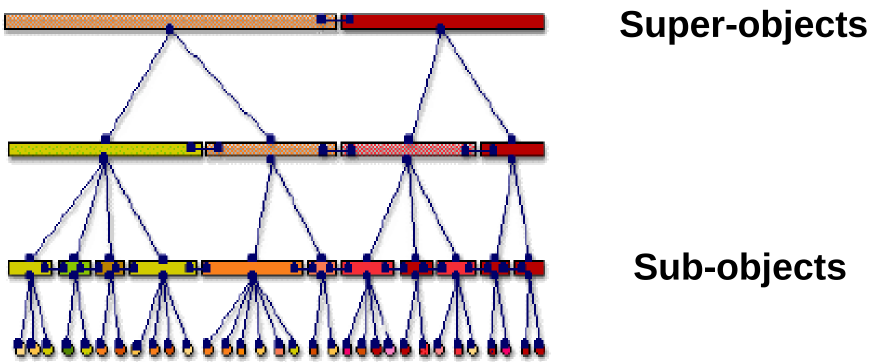


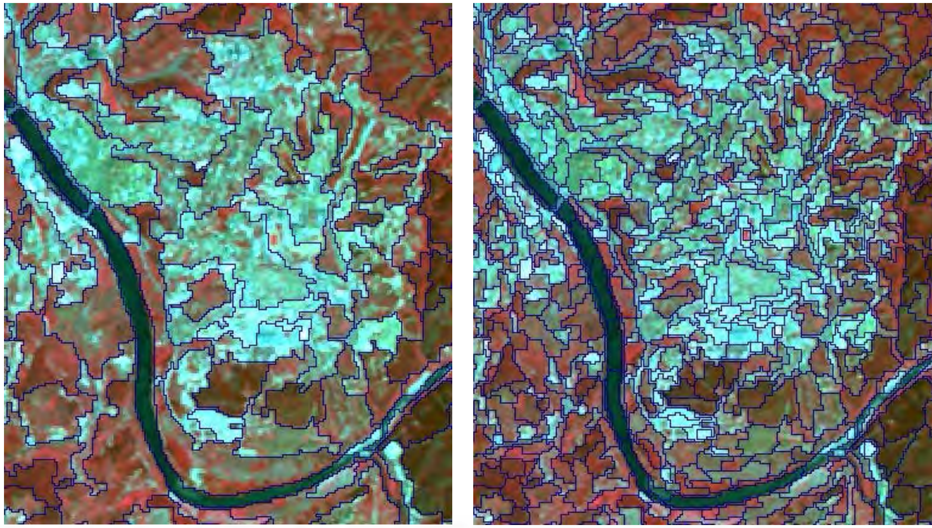


There are no “right” or “wrong” solutions to the delineation of landscape objects but instead **“meaningful” and “useful” heuristic approximations** of partitions of space.

3. Image segmentation

A type of segmentation that is very common is the **multi-resolution segmentation**, because of its ability to deal with the range of scales within a single image.





Thematic information extraction from satellite images

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4 **Feature identification and selection** *

5 Classification *

6 Ancillary data integration

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* mandatory

4. Feature identification and selection

What type of features can we use for information extraction?

Should we, for some reason, manipulate the feature space?

How can we select the best features for class discrimination?

Manipulation and selection of features are used to **reduce the number of features without sacrifying accuracy**

4. Feature identification and selection

Spectral measurements — *1st order measurements*

From a single date (Unitemporal approach)

From multiple dates (Multi-temporal approach

Secondary measurements derived from the image — *2nd order measurements*

Measurements of the spatial unit being classified

Measurements related to the neighbourhood

- Quantification of the spatial variability within the neighbourhood
  - Texture
  - Spatial features
- Semantic relationships of a spatial unit with its neighbours

Ancillary information

This term is generally used for non-spectral geographical information

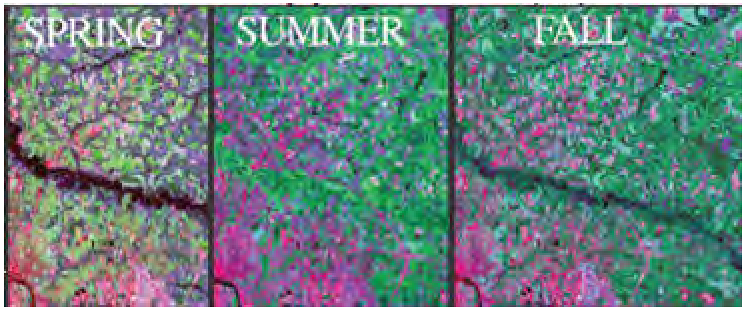
Data from images with different characteristics can also be considered as ancillary information. The approaches used for multisensor data may fall within **data fusion**.

4. Feature identification and selection

1st order measurements

Unitemporal approach

Multi-temporal approach



The production of the US National Land Cover Database (NLCD) – 2001 is based on a multi-temporal approach

It helps to discriminate classes with different phenology

Irrigated and rain fed agriculture

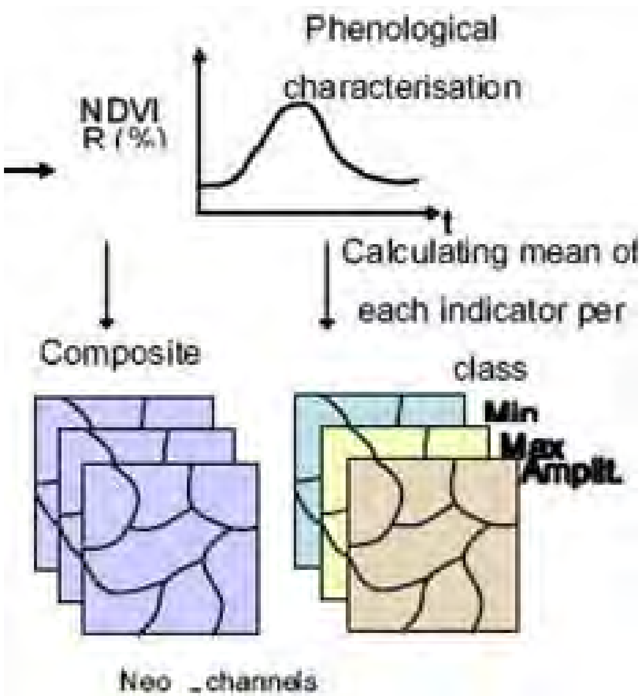
Permanent and deciduous forests

Source: Homer et al. (2004)

4. Feature identification and selection

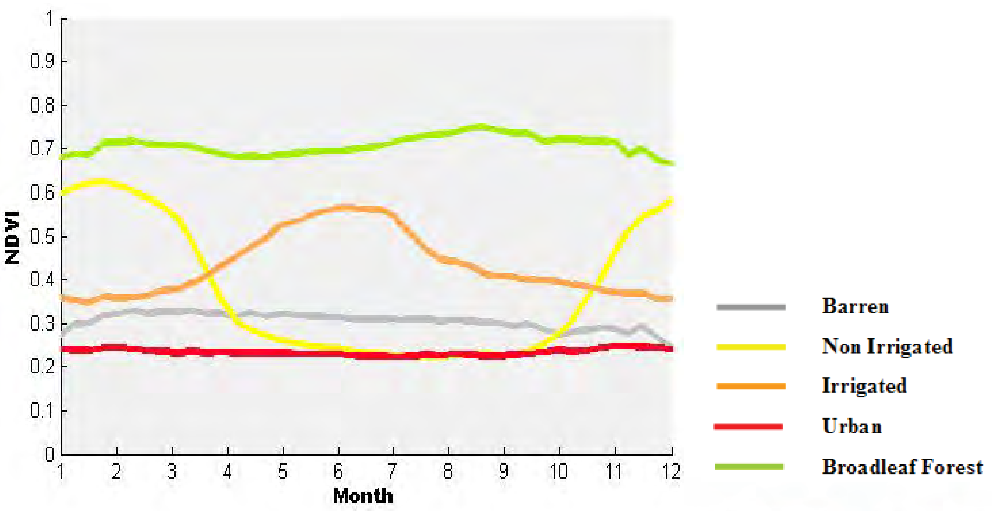
2nd order measurements

Measurements of the spatial unit being classified



Source: Defourny et al. (2005)

In the GLOBCOVER project (ESA) a set of new-channels based on the annual NDVI profile are derived.



4. Feature identification and selection

2nd order measurements

Measurements related to the neighbourhood (contextual information)

Most mapping approaches operate at a **pixel level**, ignoring its context

Contextual information and semantic relationships with neighbours is always used by photo-interpreters in **visual analysis**.

Several attempts have been carried out to take into automatic classification the contextual information.

Texture

First order statistics in the spatial domain

(e.g. mean, variance, standard deviation, entropy)

Second order statistics in the spatial domain

(e.g. homogeneity, dissimilarity, entropy, angular second moment, contrast, correlation)

Geostatistics

(e.g., variogram, correlogram, covariance function)

Fractals

4. Feature identification and selection

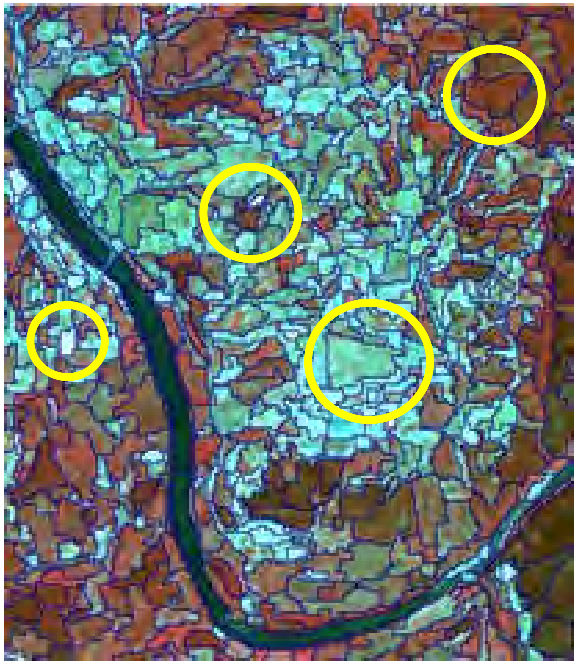
…some considerations on object oriented image classification

In **object oriented image classification** one can use features that are very similar to the ones used on visual image interpretation

Shape and size of the objects

Spectral homogeneity within objects

Semantic relationships of a spatial unit with its neighbours



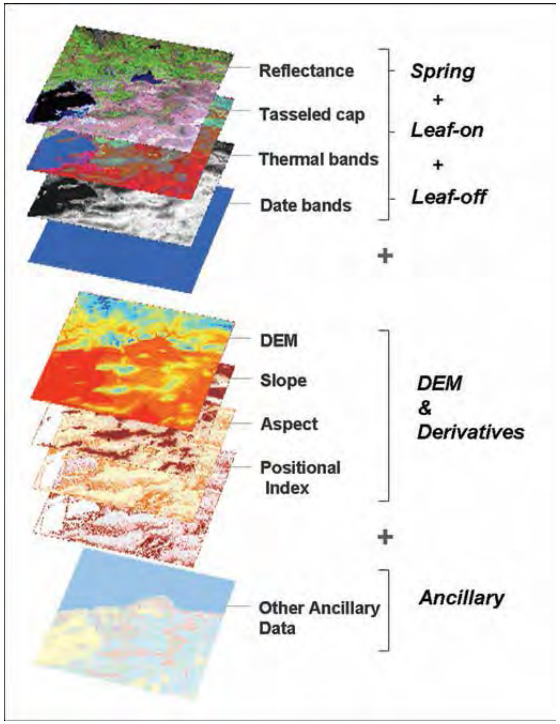
Before object oriented image classification there was the **per-field classification**. In this approach the objects are not extracted from the satellite image through segmentation but instead from an existent geographical data base with landscape units, i.e. fields.

4. Feature identification and selection

Ancillary information

continuous e.g. elevation, slope, aspect

categorical e.g. soil type, existent land cover maps



→ **US National Land Cover Database 2001**

Source: Homer et al. (2007)

Thematic information extraction from satellite images

1 Definition of the mapping approach *

2 Geographical stratification

3 Image segmentation

4 Feature identification and selection *

5 **Classification** *

6 Ancillary data integration

7 Post-classification processing

8 Accuracy assessment *

* mandatory

5. Classification

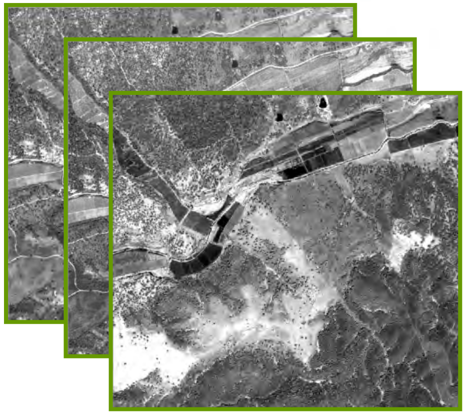
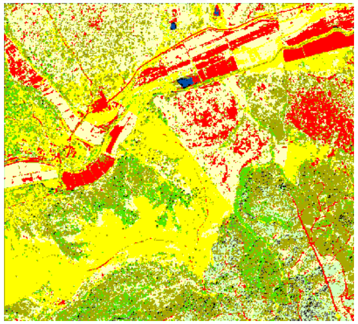


Image spatial space

Allocation of a class to each spatial unit of analysis (SUA)



Map of categorical classes

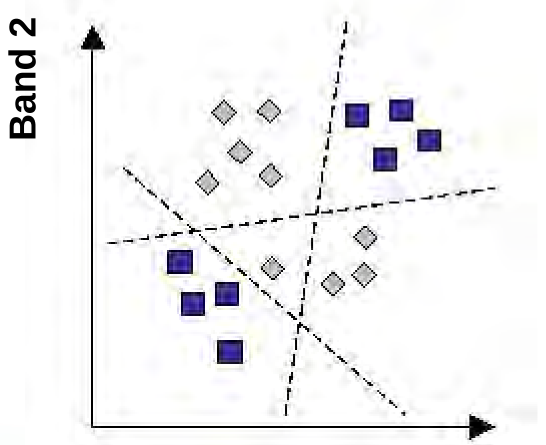


Image feature space

Each SUA is represented by a **vector**, consisting of a set of measurements (e.g. reflectance)

Definition of **decision boundaries** to separate classes

Definition of the **decision rule**, i.e. the algorithm that defines the position of a SUA with respect to the decision boundaries and that allocates a specific label to that SUA

The word **classifier** is widely used as a synonym of the term decision rule

5. Classification

Artificial intelligence

Data mining

Computer sciences

Statistics

Pattern recognition

Machine learning

- satellite image classification

- natural language processing
- syntactic pattern recognition
- search engines
- medical diagnosis
- bioinformatics
- cheminformatics
- stock market analysis
- classifying DNA sequences
- speech recognition,
- handwriting recognition
- object recognition in computer vision
- game playing
- robot locomotion

5. Classification

Different possibilities to categorise classifiers

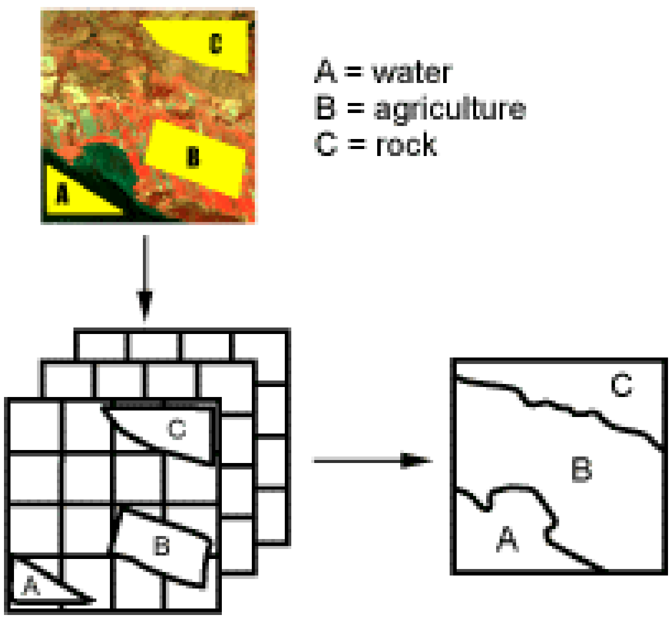
- Type of learning
  - supervised
  - unsupervised
- Assumptions on data distribution
  - Parametric
  - Non-parametric
- Number of outputs for each spatial unit
  - Hard (crisp)
  - Soft (fuzzy)

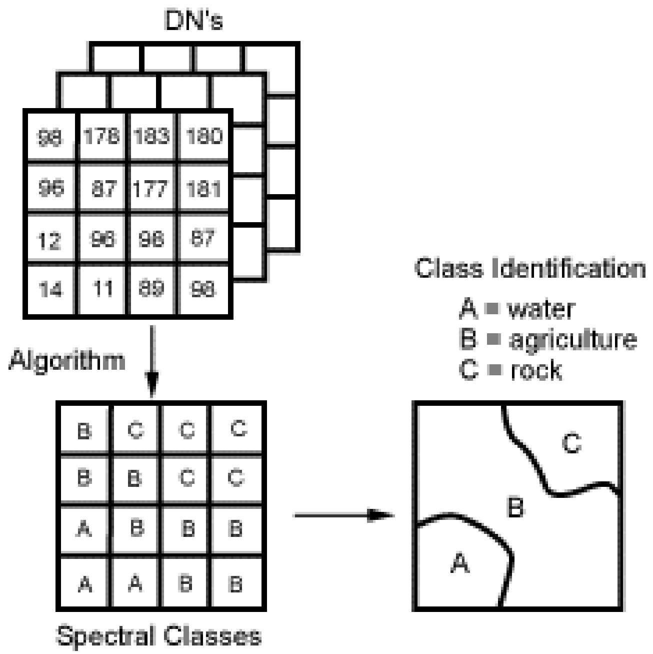
5. Classification

Type of learning

Supervised classification

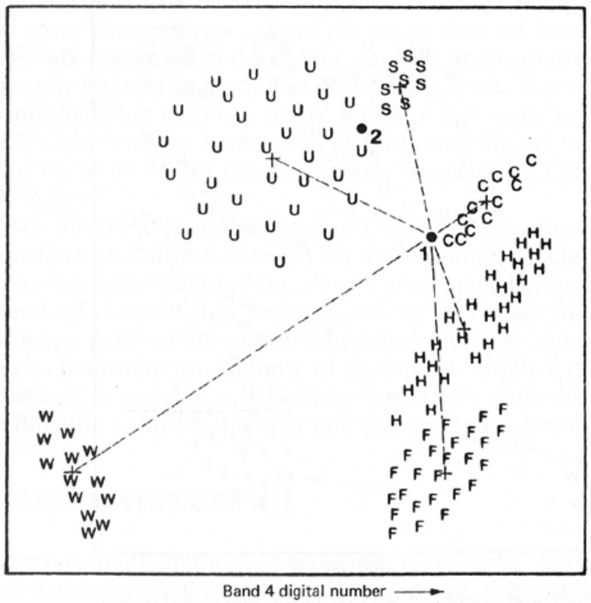
Unsupervised classification



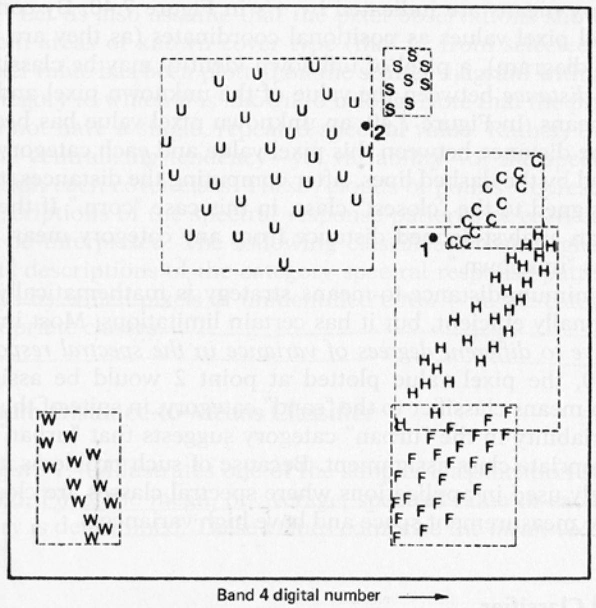


Source: CCRS

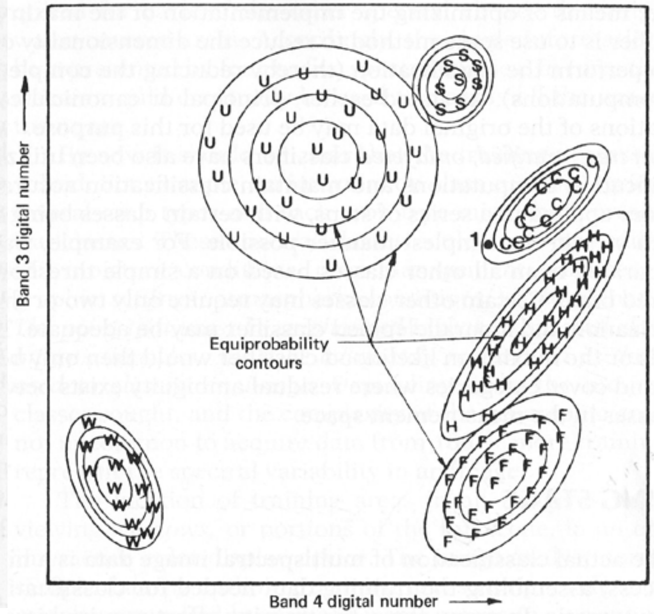
5. Classification
Classic supervised classifiers



Minimum distance



Parallelepiped



Maximum likelihood

Source: Jensen (1996)

5. Classification

Most important advanced supervised classifiers

- Maximum likelihood
- Nearest neighbour
- Artificial neural networks
- Decision trees
- Support vector machines
- Spectral Mixture Analysis

Source: Jensen et al. (2009), Lu and Weng (2007), Wilkinson (2005)

5. Classification

Some considerations on the training stage…

- The **training phase is decisive** on the final results of image classification. In fact, in thise phase we collect the data that will be used to train the algorithm.

- The usual **restrictions on sampling** (cost, availability of data and accessibility) may lead to an **inadequate sampling**.

- In case of **parametric** classifiers the **number of sample observations** affect strongly the estimates of the **statistical parameters**.

- As the dimensionality of the data increases for a fixed sample size so the precision of the statistical parameters become lower (i.e., **Hughes phenomenon**).

- It is common that even **mixed pixels dominate the image**, only **pure pixels** are selected for training. However, this may lead to unsatisfactory classification accuracy.

5. Classification

Assumptions on data distribution

Parametric classifiers

e.g., maximum likelihood classifier

Non-parametric classifiers

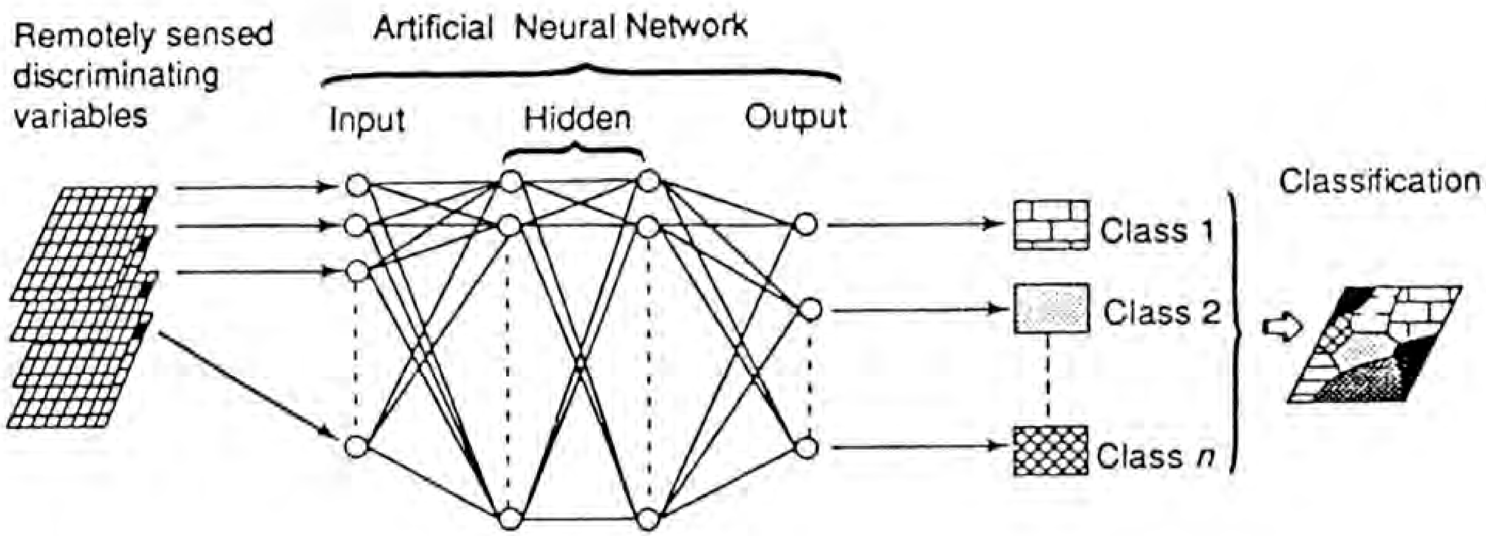
e.g., decision trees, artificial neural networks, support vector machines, nearest neighbour

- Traditionally most classifiers have been grounded to a significant degree in **statistical decision theory**.
- These classifiers rely on **assumptions of data distribution**.
- The **performance** of a parametric classifier depends largely on how well the data match the pre-defined models and on the accuracy of the estimation of the model parameters.
- They suffer from the **Hughes phenomenon** (i.e. curse of dimensionality), and consequently it might be difficult to have a significant number of training pixels.
- They are not adequate to integrate **ancillary data** (due to difficulties on classifying data at different measurement scales and units).

5. Classification Non-parametric classifiers Artificial Neural Networks

An ANN is a form of artificial intelligence that imitates some functions of the human brain.

An ANN consists of a series of layers, each containing a set of processing units (i.e. neurones)



All neurones on a given layers are linked by weighted connections to all neurones on the previous and subsequent layers.

During the training phase, the ANN learns about the regularities present in the training data, and based on these regularities, constructs rules that can be extended to the unknown data

Source: Foody (1999)

5. Classification Non-parametric classifiers Artificial Neural Networks

Most common types of ANN

- Multi-layer perceptron with back-propagation
- Self-organised feature map (SOM)
- Hopfield networks
- ART (Adaptive Ressonance Theory) Systems

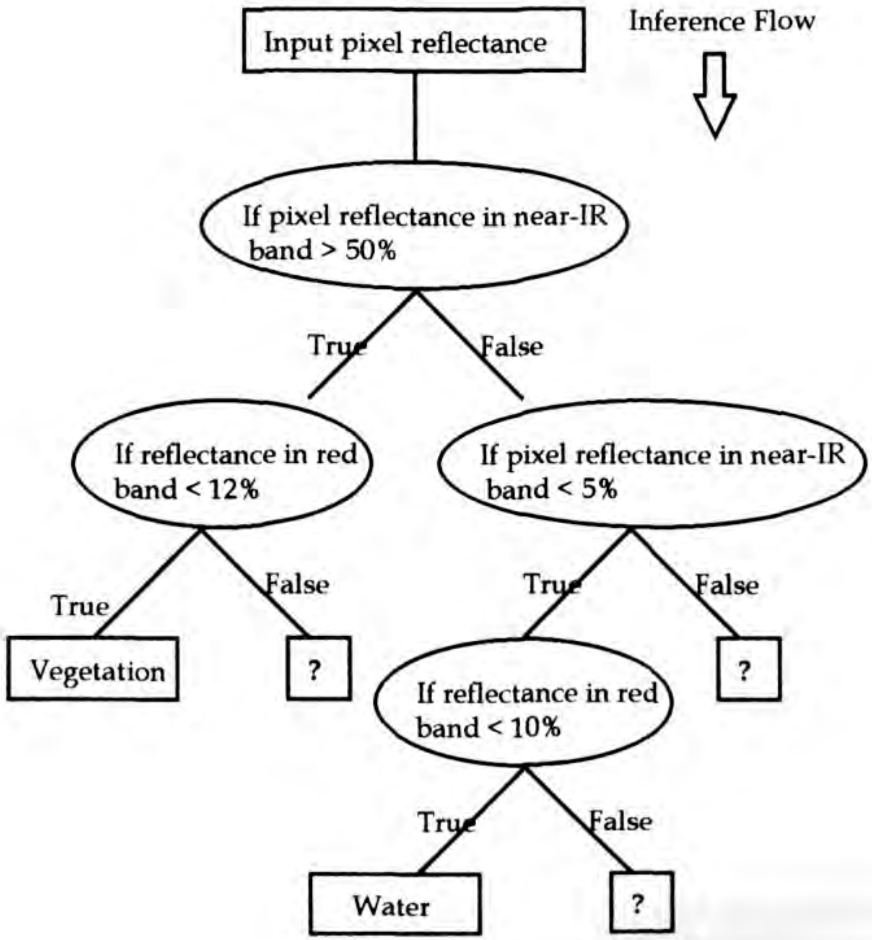
Advantages of ANN

- It is a **non-parametric classifier**, i.e. it does not require any assumption about the statistical distribution of the data.
- **High computation rate**, achieved by their massive parallelism, resulting from a dense arrangement of interconnections (weights) and simple processors (neurones), which permits real-time processing of very large datasets.

Disadvantages of ANN

- ANN are **semantically poor**. It is difficult to gain any understanding about how the result was achieved.
- The **training** of an ANN can be computationally demanding and slow.
- ANN are perceived to be **difficult to apply successfully**. It is difficult to select the type of network architecture, the initial values of parameters (e.g., learning rate, the number of iterations, initial weights)

Non-parametric classifiers — Decision Trees



DT are knowledge based (i.e. a method of pattern recognition that simulates the brains inference mechanism).

DT are hierarchical rule based approaches.

DT predict class membership by recursively partitioning a dataset into homogeneous subsets.

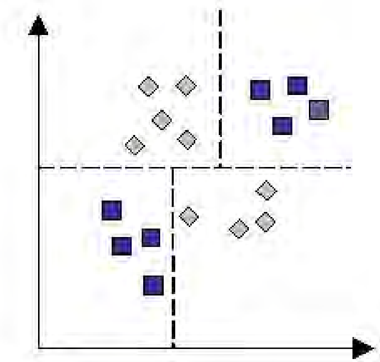
Different variables and splits are then used to split the subsets into further subsets.

There are hard and soft (fuzzy) DT.

Source: Tso and Mather (2001)

Advantages of DT

- Ability to handle **non-parametric** training data, i.e. DT are not based on any assumption on training data distribution.
- DT can reveal **nonlinear and hierarchical** relationships between input variables and use these to predict class membership.
- DT yields a set of rules which are **easy to interpret** and suitable for deriving a physical understanding of the classification process.
- DT, unlike ANN, **do not need an extensive** design and training
- Good **computational efficiency**.



Disadvantages of DT

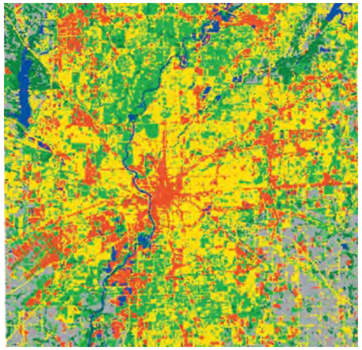
- The use of hyperplane **decision boundaries parallel to the feature** axes may restrict their use in which classes are clearly distinguishable.

5. Classification

Number of outputs for each spatial unit

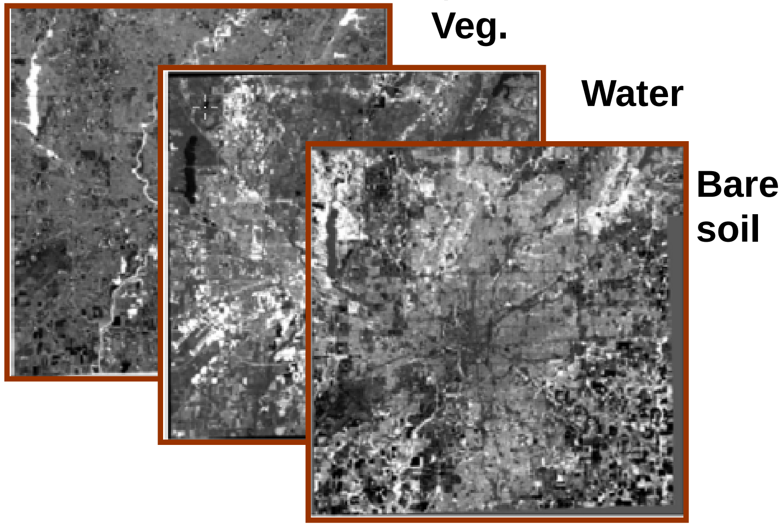
Hard (crisp) classification

each pixel is forced or constrained to show membership to a single class.



Soft (fuzzy) classification

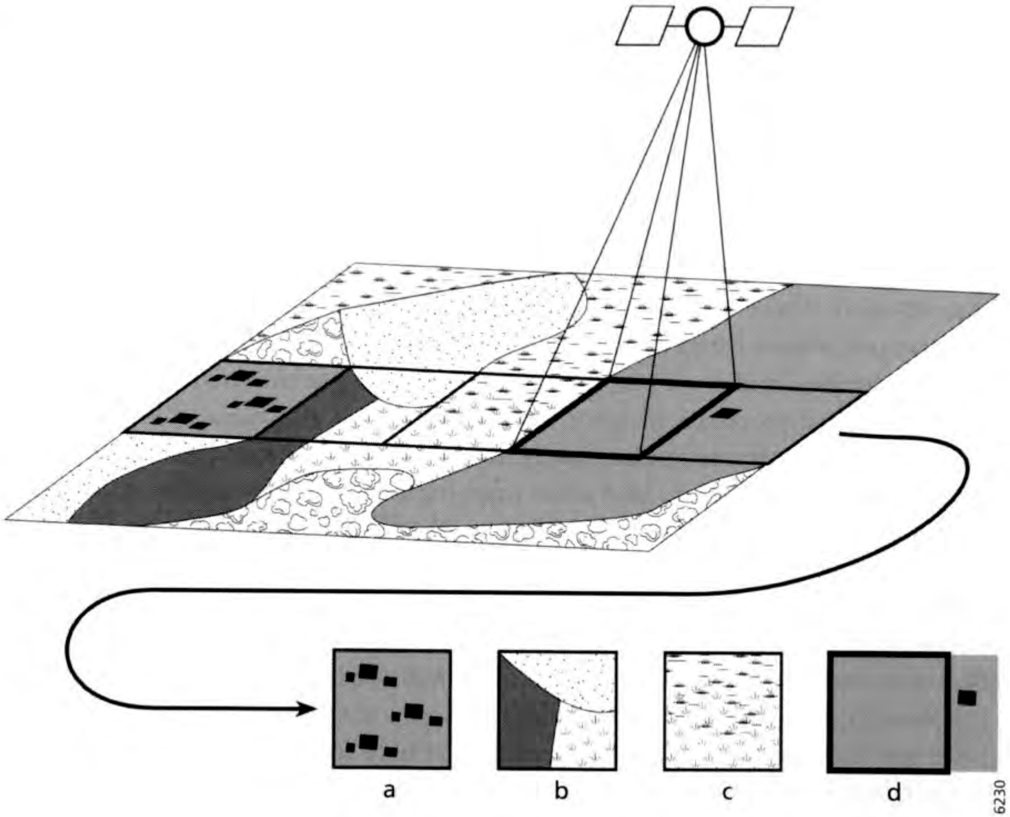
each pixel may display multiple and partial class membership.



Soft classification has been proposed in the literature as an alternative to hard classification because of its ability to deal with **mixed pixels**.

5. Classification

The mixed pixel problem

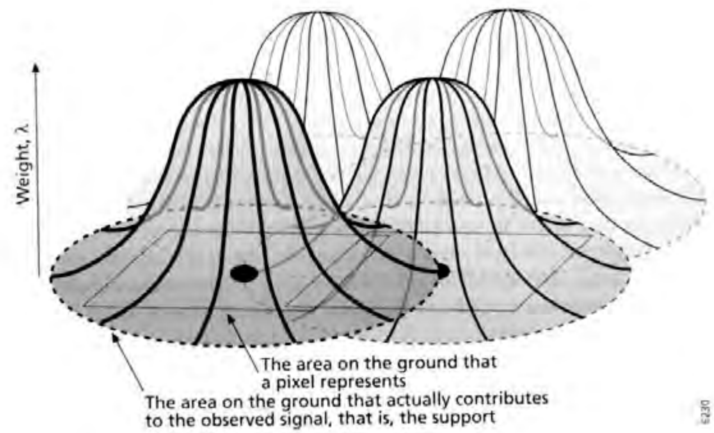


A – presence of small, sub-pixel targets

B – presence of boundaries of discrete land cover classes

C – gradual transition between land cover classes (continuum)

D – contribution of areas outside the area represented by a pixel



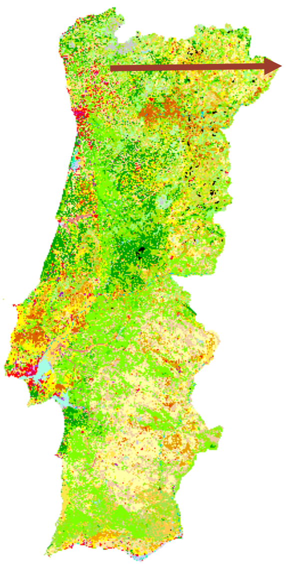
Source: Foody (2004)

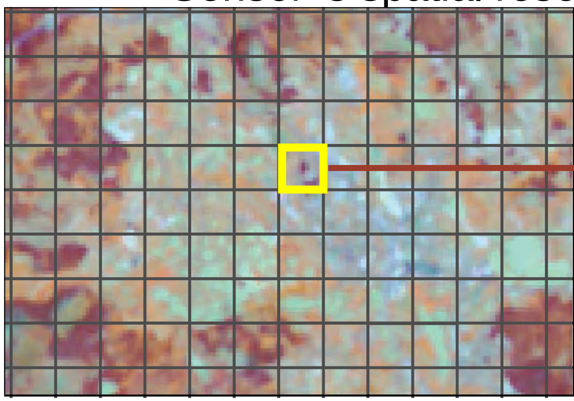
5. Classification

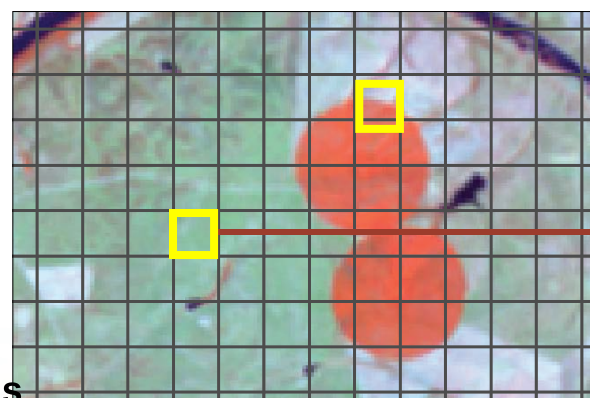
The mixed pixel problem

The number of mixed pixels in an image varies mainly with:

Landscape fragmentation
Sensor's spatial resolution







MERIS FR pixels

The problem of mixed pixels exist in coarse and fine resolution images:

In course resolution images the mixed pixels are mainly due to co-existence in the same pixel of different classes.

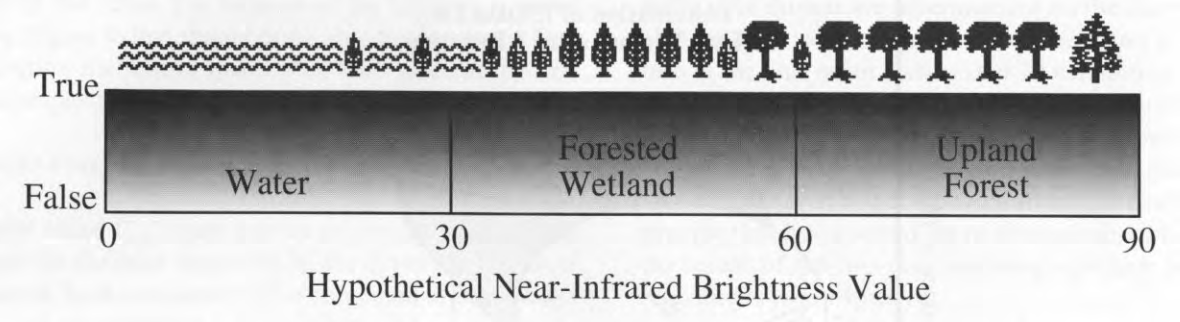
MERIS FR

In fine resolution images the mixed pixels are mainly due to co-existence in the same pixel of different components (e.g., houses, trees).

IKONOS

5. Classification

Hard classification



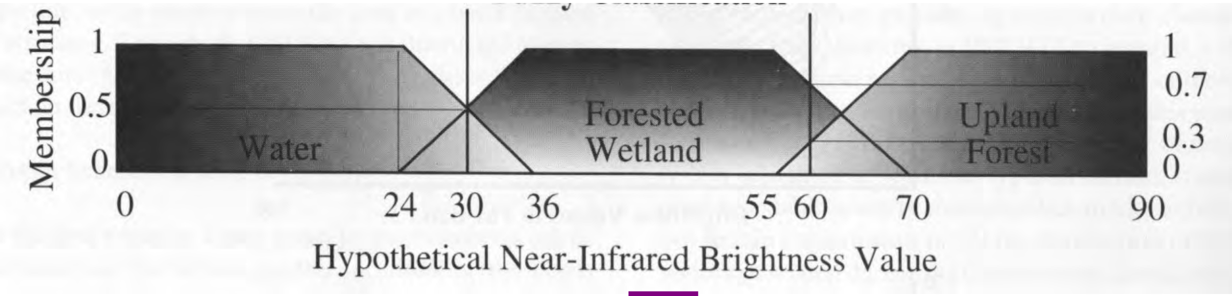
Decision rules

0 – 30 -> Water

30 - 60 -> Forest wetland

60 - 90 -> Upland forest

Fuzzy classification



Decision rules are defined as membership functions for each class.

Membership functions allocates to each pixel a real value between 0 and 1, i.e. membership grade.

But, wow can we represent the sub-pixel information?

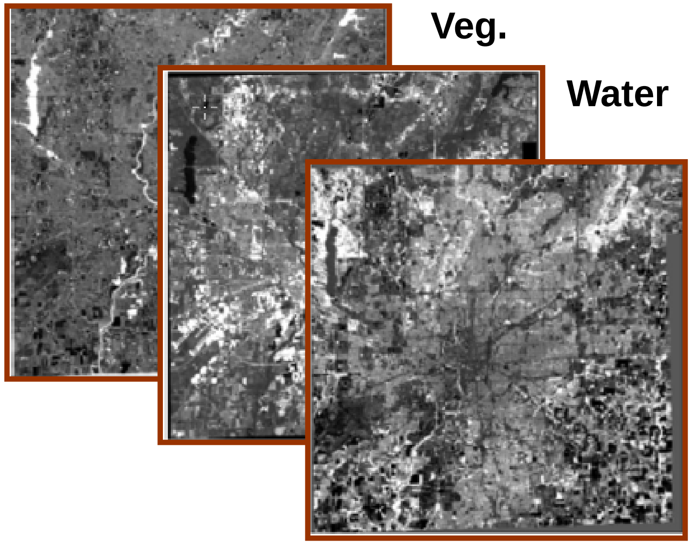
Source: Jensen (1996)

5. Classification

How can we represent the sub-pixel information?

Sub-pixel scale information is typically represented in the output of a soft classification by the **strength of membership a pixel displays to each class.**

It is used to reflect the relative proportion of the classes in the area represented by the pixel



5. Classification

How can we represent the sub-pixel information?

Map with primary and secondary classes

Entropy image

The pixel value translates a degree of mixing (entropy is minimised when the pixel is associated with a single class and maximised when membership is partitioned evenly between all of the defined classes).

Hill's diversity numbers image

The pixel values provides information on the number of classes, the number of abundant classes and the number of very abundant classes.

5. Classification

Soft classifiers

Most common soft classifiers

- Maximum likelihood classification
- Fuzzy c-means
- Possibilistic c-means
- Fuzzy rule based classifications
- Artificial neural networks

Approaches based on fuzzy set theory

Maximum likelihood classifier (MLC)

- MLC is one of the **most widely** used hard classifier.
- In a standard MLC each pixel is allocated to the class with which it has the **highest posterior probability of class membership**.
- MLC has been adapted for the derivation of **sub-pixel information**.
- This is possible because a **by-product** of a conventional MLC are the **posterior probabilities** of each class for each pixel.
- The posterior probability of each class provides is a relative measure of **class membership**, and can therefore be used as an **indicator of sub-pixel proportions**.
- Some authors use the term **Fuzzy MLC**, to discriminate it from the (hard) MLC.

Conceptually, there is not a direct link between the proportional coverage of a class and its posterior probability. In fact, posterior probabilities are an indicator of the uncertainty in making a particular class allocation. However many authors have find that in practice useful sub-pixel information can be derived from this approach.

Soft classifiers

The continuum of classification fuzziness

In the literature the term fuzzy classification has been used for cases where fuzziness is only applied to the allocation stage – which does not seem to be completely correct.

If we apply the concept of fuzziness to all stages of image classification we can create a continuum of fuzziness, i.e. a range of classification approaches of variable fuzziness.

Completely-crisp classification	→ Classification stages	**Fully-fuzzy classification**
Dominant class	Training →	Individual class proportions
Pixel is allocated to a single class	Allocation →	Membership grade to all classes
Dominant class	Testing →	Individual class proportions

Source: Foody (2004)

5. Classification

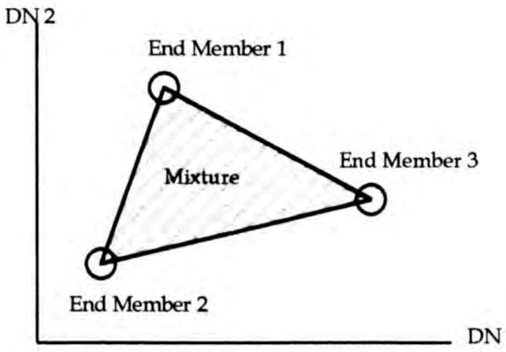
Spectral unmixing

Spectral unmixing = spectral mixture modelling = spectral mixture analysis

Spectral unmixing is an alternative to soft classification for sub-pixel analysis.

Spectral unmixing is based on the **assumption that spectral signature of satellite images results essentially from a** mixture of a small number of pure components (endmembers) with characteristic spectra.

If so, it is then possible to use a limited number of components so that mixtures of these component spectra adequately simulate the actual observations.



Source: Tso and Mather (2000)

Linear mixture models are the most common models used in satellite image analysis

$$DN_c = \sum_{1}^{N} F_n DN_{n_1 c} + E_c$$

DNc –image radiance for band c
N – is the number of endmembers
F_n – is the relative fraction of endmember n
$DNn.c$ – is the endmember n inner radiance
Ec –residual fitting error

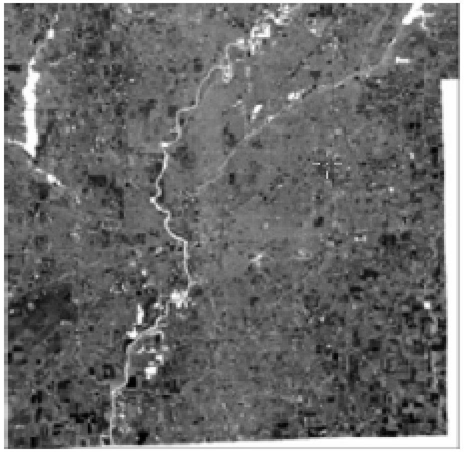
Spectral unmixing

A case study: urban mapping

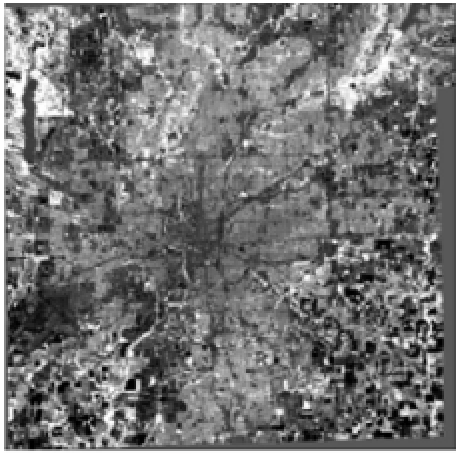
Lu and Weng (2004) used Spectral Mixture Analysis for mapping the Urban Landscape in Indianapolis with Landsat ETM+ Imagery.

SMA was used to derive fraction images to three endmembers: shade, green vegetation, and soil or impervious surface

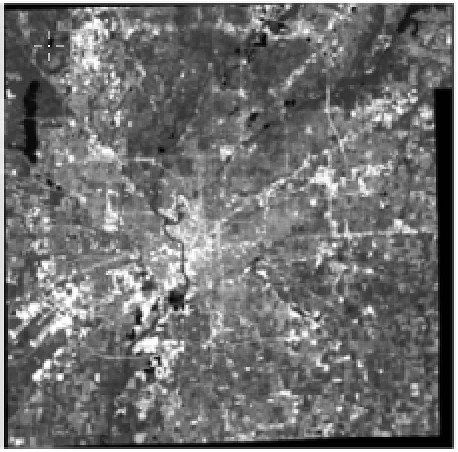
Output of spectral unmixing



Shade fraction

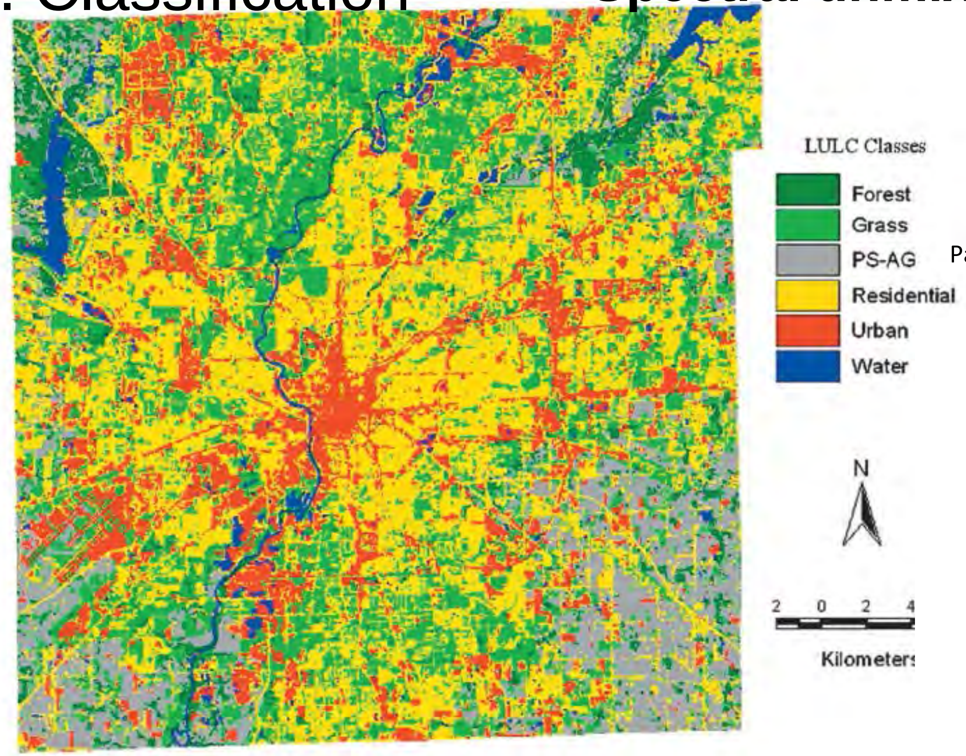


Vegetation fraction



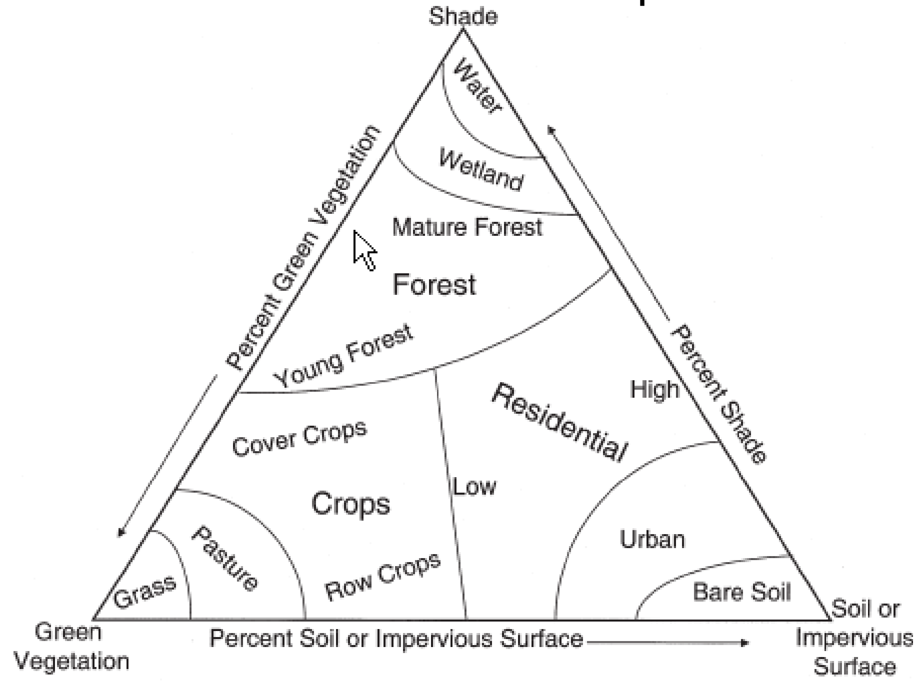
Soil or impervious surface fraction

5. Classification **Spectral unmixing** **A case study: urban mapping**



Pasture and Agricultural lands

Lu-Weng urban landscape model



The fraction images were used to classify LCLU classes based on a hybrid procedure that combined maximum-likelihood and decision-tree algorithms.

Source: Lu and Weng (2004)

Sub-pixel classification Super-resolution mapping

Although classification at sub-pixel level is informative and meaningful it fails to account for the spatial distribution of **class** proportions within the pixel.

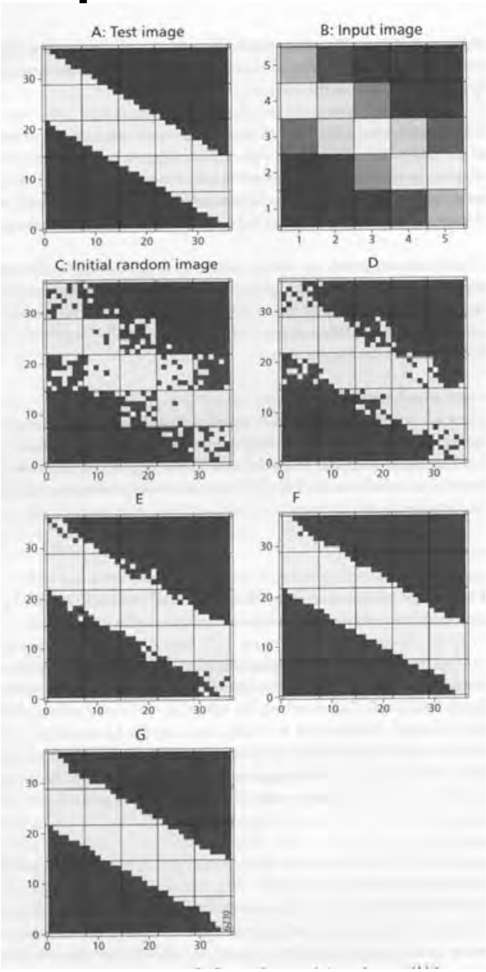
Super-resolution mapping (or sub-pixel mapping) is a step forward.

Super-resolution mapping considers the spatial distribution within and between pixels in order to produce maps at sub-pixel scale.

Several approaches of super-resolution mapping have been developed:

- Hopfield neural networks
- Pixel-swapping solution (based on geostatistics)
- Linear optimization
- Markov random fields

Sub-pixel classification Super-resolution mapping



Pixel-swapping solution – this technique allows sub-pixel classes to be swapped within the same pixel only.

Swaps are made between the most and least attractive locations if they result in **an increase in spatial correlation** between sub-pixels.

Source: Atikson (2004)

Multiple classifiers approach

Rationale

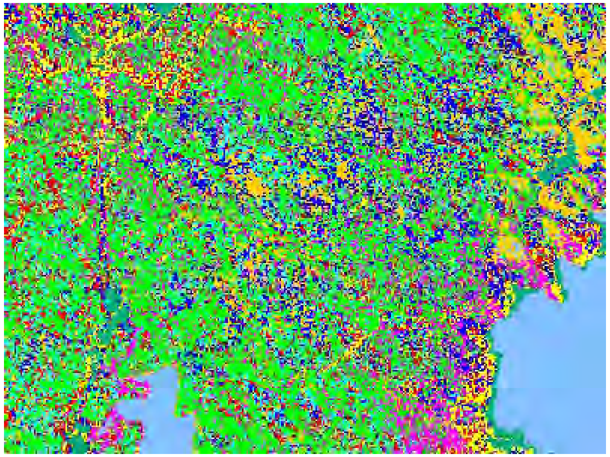
- Different classifiers originate different classes for the same spatial unit
- There are several studies on the comparison of different classifiers
- There is not a single classifier that performs best for all classes. In fact it appears that many of the methods are complementary
- Combination of decision rules can bring advantages over the single use of a classifier

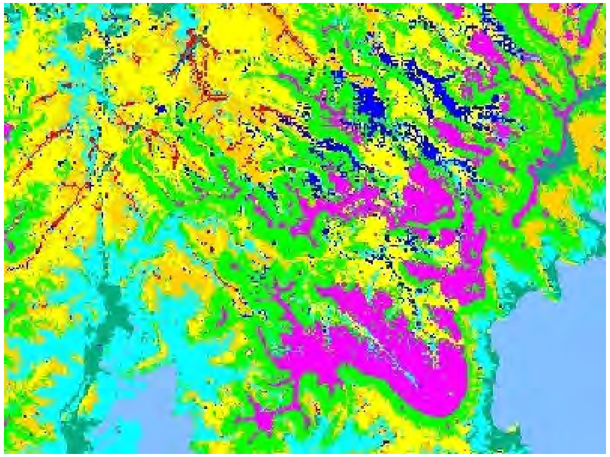
In the multiple classifiers approach the classifiers should be independent. To be independent the classifiers must use ***an independent feature set*** *or be trained on* ***separate sets of training*** *data.*

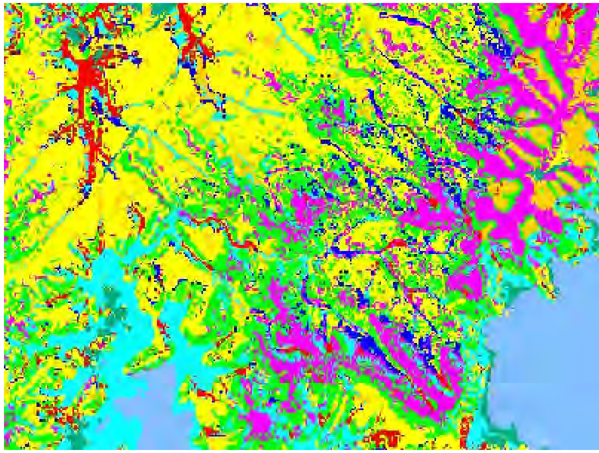
5. Classification

Multiple classifiers approach

How different the results from different classifiers can be?


Maximum likelihood


Artificial Neural Networks


Decision tree

Source: Gahegan and West (1998)

Multiple classifiers approach

Methods for combining classifiers

Voting rules

The label outputs from different classifiers are collected and the majority label is selected (i.e. **majority vote rule**). There are some variants, such as the comparative majority voting (it requires that the majority label should exceed the 2nd more voted by a specific number).

Bayesian formalism

It is used with multiple classifiers that output a probability. The probabilities for a spatial unit for each class resulting from different classifiers are accumulated and the final label is the one that has the greatest **accumulated probability**.

Evidential reasoning

It associates a **degree of belief** with each source of information, and a formal system of rules is used in order to manipulate the belief function.

Multiple neural networks

It consists on the use of a neural network to produce a single class to each spatial unit, **fed with the outputs** from different classifiers.

Thematic information extraction from satellite images

1 Definition of the mapping approach *

2 Geographical stratification

3 Image segmentation

4 Feature identification and selection *

5 Classification *

6 **Ancillary data integration**

7 Post-classification processing

8 Accuracy assessment *

* mandatory

6. Ancillary data integration

Ancillary data can be integrated after image classification in order to improve the results.

Post-classification sorting - application of very specific rules to classification results and to geographical ancillary data (e.g., elevation, slope, aspect)

There are several strategies based on expert systems, rule based systems and knowledge base systems

Thematic information extraction from satellite images

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* mandatory

7. Post-classification processing

Post processing is required in two cases

The Minimum Mapping Unit of the very final map is larger than the spatial unit used in the classification

Map generalisation

Upscaling

The final map has a vector format and the Spatial Unit of Analysis was the pixel

Raster to vector conversion

7. Post-classification processing

The steps required to information extraction depend on the defined mapping approach:

Map format = raster

MMU = pixel size of input satellite data

Feature selection > Image classification > accuracy assessment

MMU > pixel size of input satellite data

Feature selection > Image classification > post-processing > accuracy assessment

upscaling

Map format = vector

Spatial unit of analysis = image pixel

Feature selection > Image classification > post-processing > accuracy assessment

Generalisation + Raster to vector conversion

Spatial unit of analysis = object

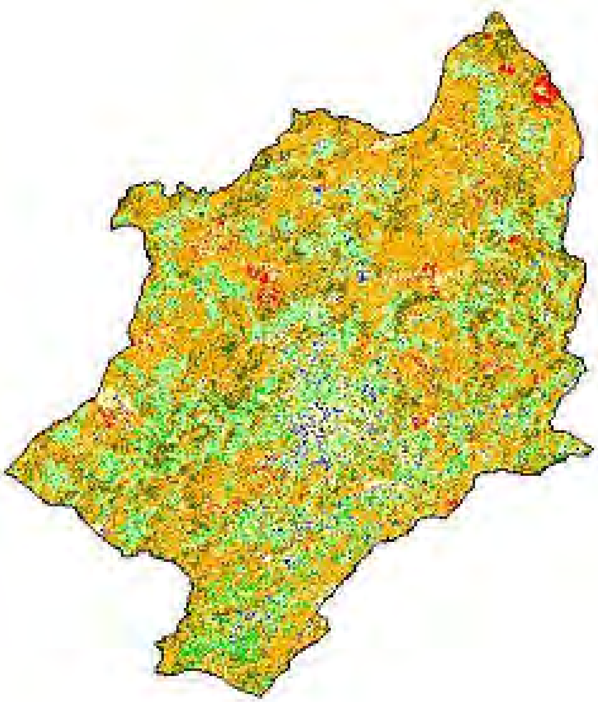
Image segmentation > Feature selection > Image classification > post-processing > accuracy assessment

Generate the objects

Generalisation

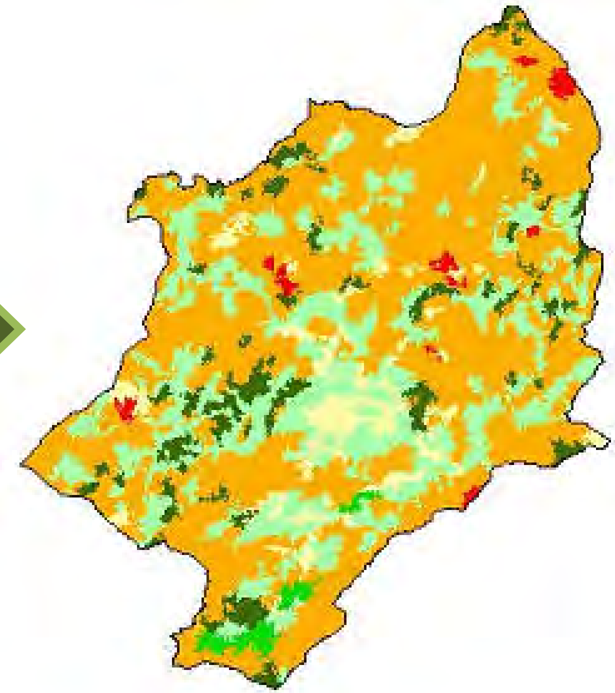
7. Post-classification processing

Semantic generalisation



MMU = 1 pixel (30mx30m)

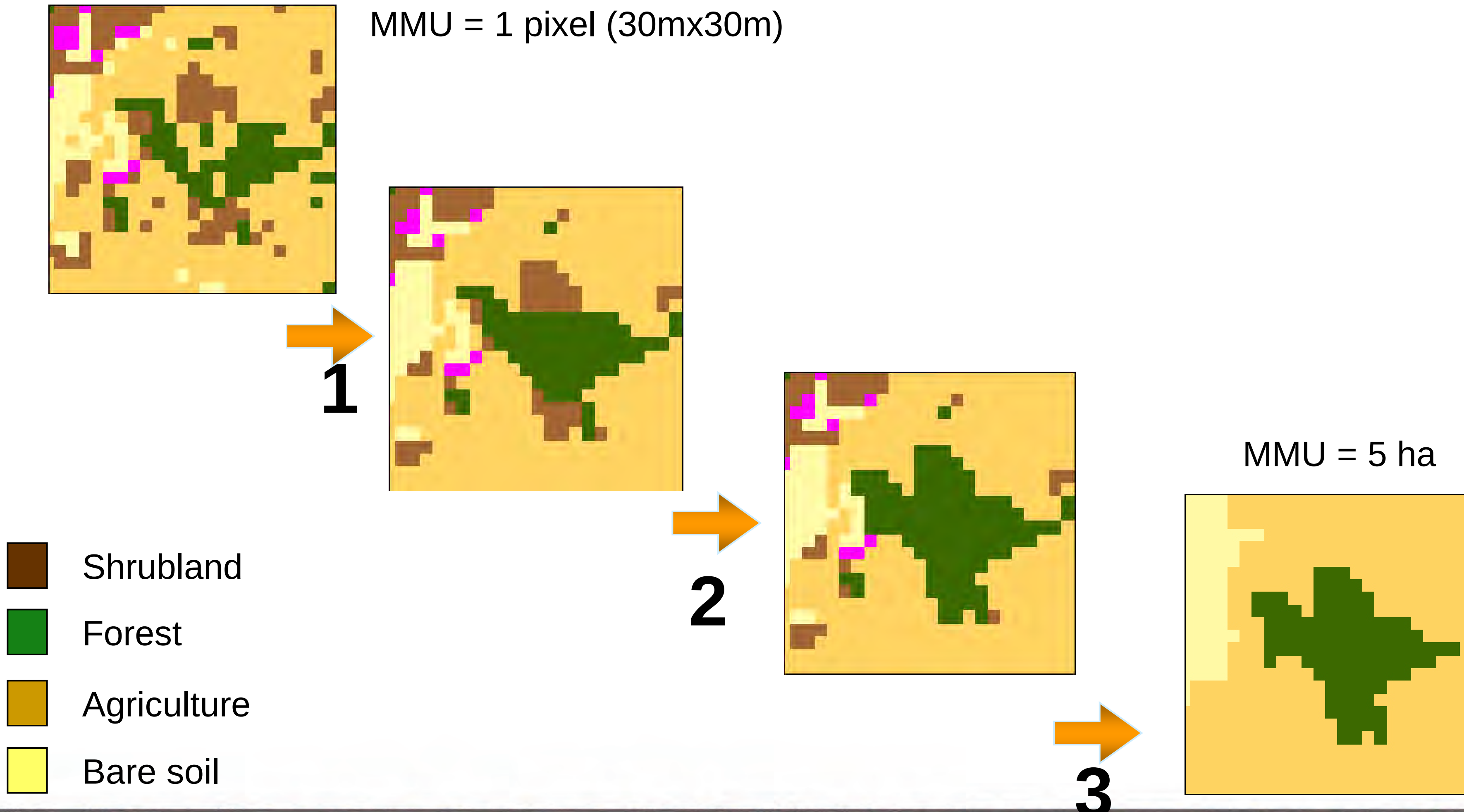
Semantic generalisation



MMU = 5 ha

7. Post-classification processing

Semantic generalisation



Thematic information extraction from satellite images

1 Definition of the mapping approach *

2 Geographical stratification

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5 Classification *

6 Ancillary data integration

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8 **Accuracy assessment** *

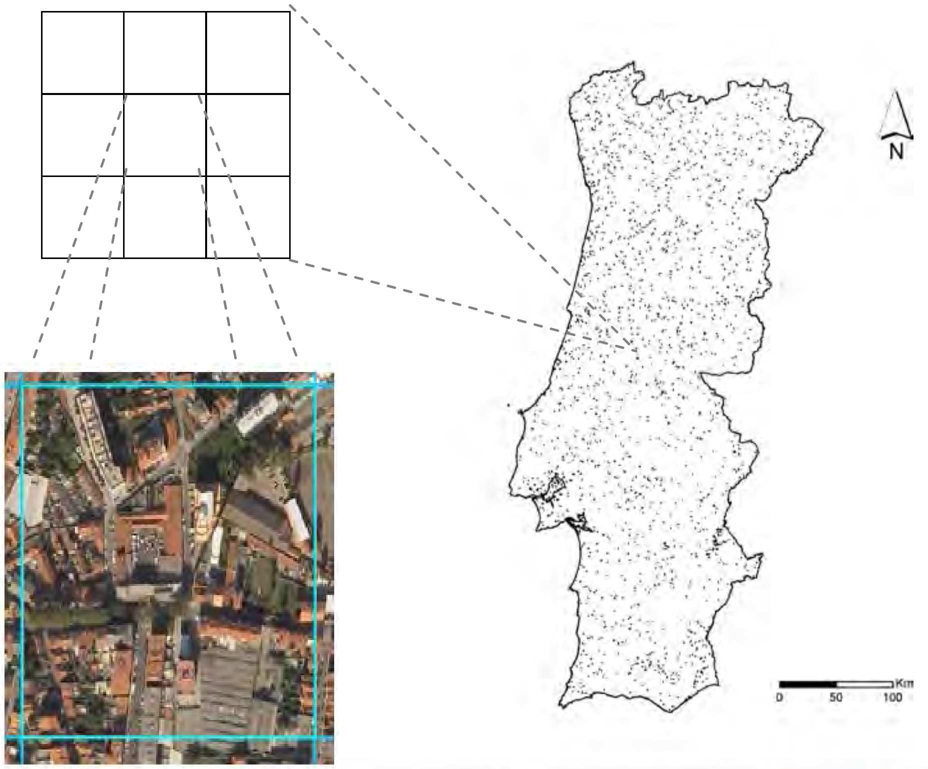
* mandatory

8. Accuracy assessment

Accuracy assessment allows users to evaluate the utility of a thematic map for their intended applications.

The most widely used method for accuracy assessment may be derived from a **confusion or error matrix**.

The confusion matrix is a simple cross-tabulation of the mapped class label against the observed in the ground or reference data for a **sample set**.



8. Accuracy assessment

Main steps

1 Selection of the reference sample

sampling units

sampling design

Probability sampling is necessary if one wants to extend the results obtained on the samples to the whole map.

Probability sampling requires that all inclusion probabilities be greater than zero, e.g. one cannot exclude from sampling inaccessible areas or landscape unit borders.

2 Response design

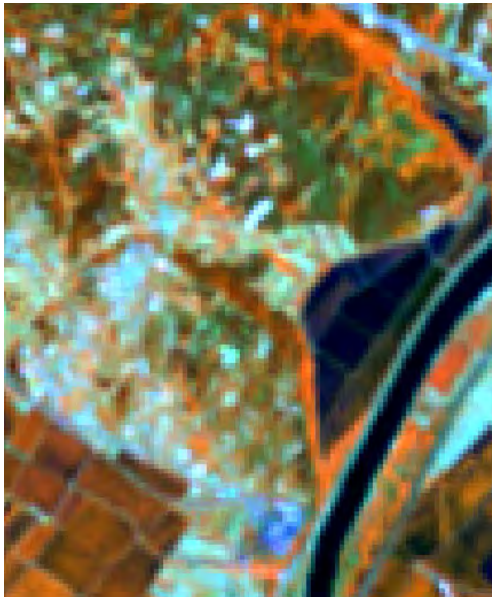
The definition of the response design depends on the process for assessing agreement (e.g., primary, fuzzy or quantitative).

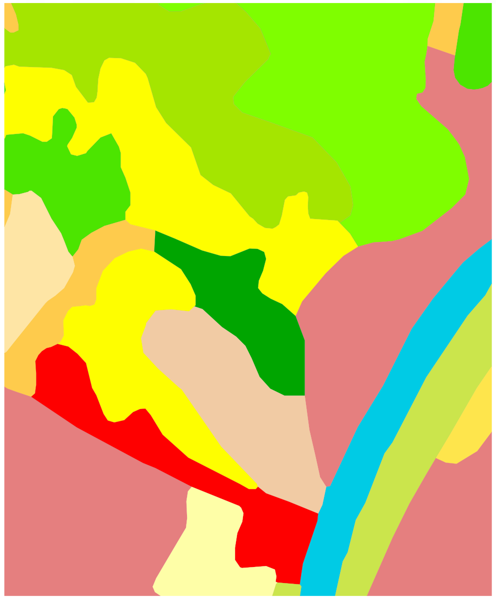
3 Analysis and estimation

One has to take into account the known areas (marginal distributions) of each map category to derive unbiased estimations of the proportion of correctly mapped individuals.

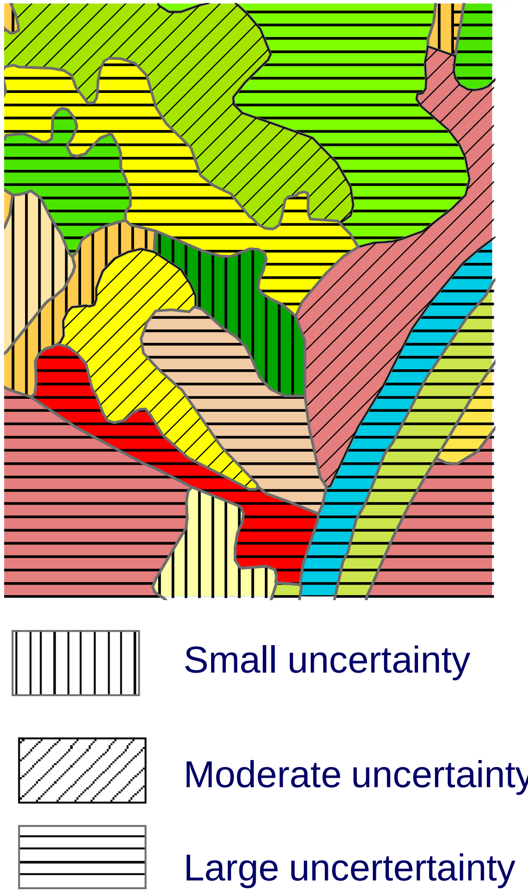
Source: Stehman (1999), Stehman and Foody (2009)

8. Accuracy assessment





Overall accuracy: **86%**



But, where is the error?

Uncertainty mapping

1 Setting the scene

2 The need for LCLU monitoring data

- LCLU: a cross-cutting environmental variable
- LCLU monitoring and environmental legislation
- Relation between two European initiatives (Copernicus and INSPIRE) and LCLU monitoring
- Hard and soft LCLU maps
- The Land Cover Classification System

3 From data to information: some important advances in LCLU monitoring

- Two different approaches for LCLU monitoring
- Spectral and class change detection
- Image classification for LCLU mapping

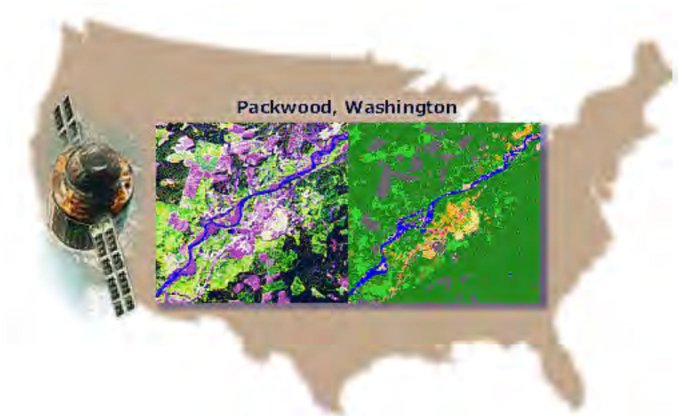
4 LCLU monitoring operational programs

- At country level (NLCD from USA)
- At European level (Land monitoring service within Copernicus)
- At Global level (GLOBCOVER)

US National Land Cover Database (NLCD)

In 1992 several federal agencies of the US agreed to operate as a consortium in order to acquire satellite-based remotely sensed data for their environmental monitoring programs, i.e. **Multi-Resolution Land Characteristics Consortium (MRLC)**

EPA NOAA USFS USGS LANDFIRE BLM NRCS NPS NASA USFWS OSM



http://www.mrlc.gov/

US National Land Cover Database (NLCD)

MCRL has been the umbrella for many US programs, which require landcover data for addressing their agency needs, namely the 2 National Land Cover Databases:

NLCD 1992 A single product: a land cover map

Vogelmann et al. (2001)

NLCD 2001 Multiple products: land cover map, land cover change 1992-2001 (retrofit), percent tree canopy and percent urban imperviousness.

Homer et al. (2004, 2007)

NLCD 2006 Multiple products: land cover map, land cover change 2001-06, and percent developed imperviousness

Fry et al. (2011)

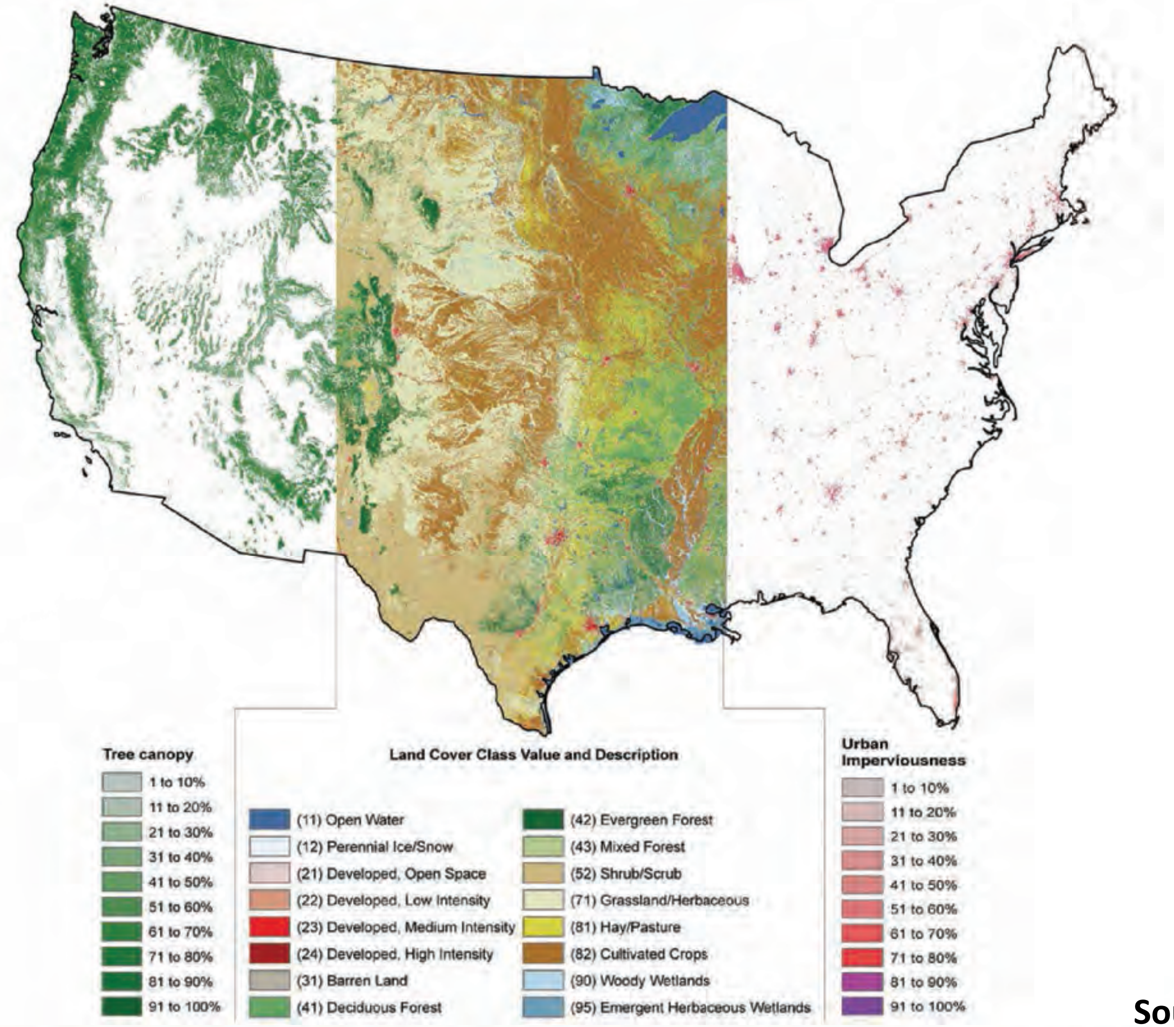
NLCD 2011 Under development (2013) http://pubs.usgs.gov/fs/2012/3020/fs2012-3020.pdf

NLCD 1992

NLCD 2001

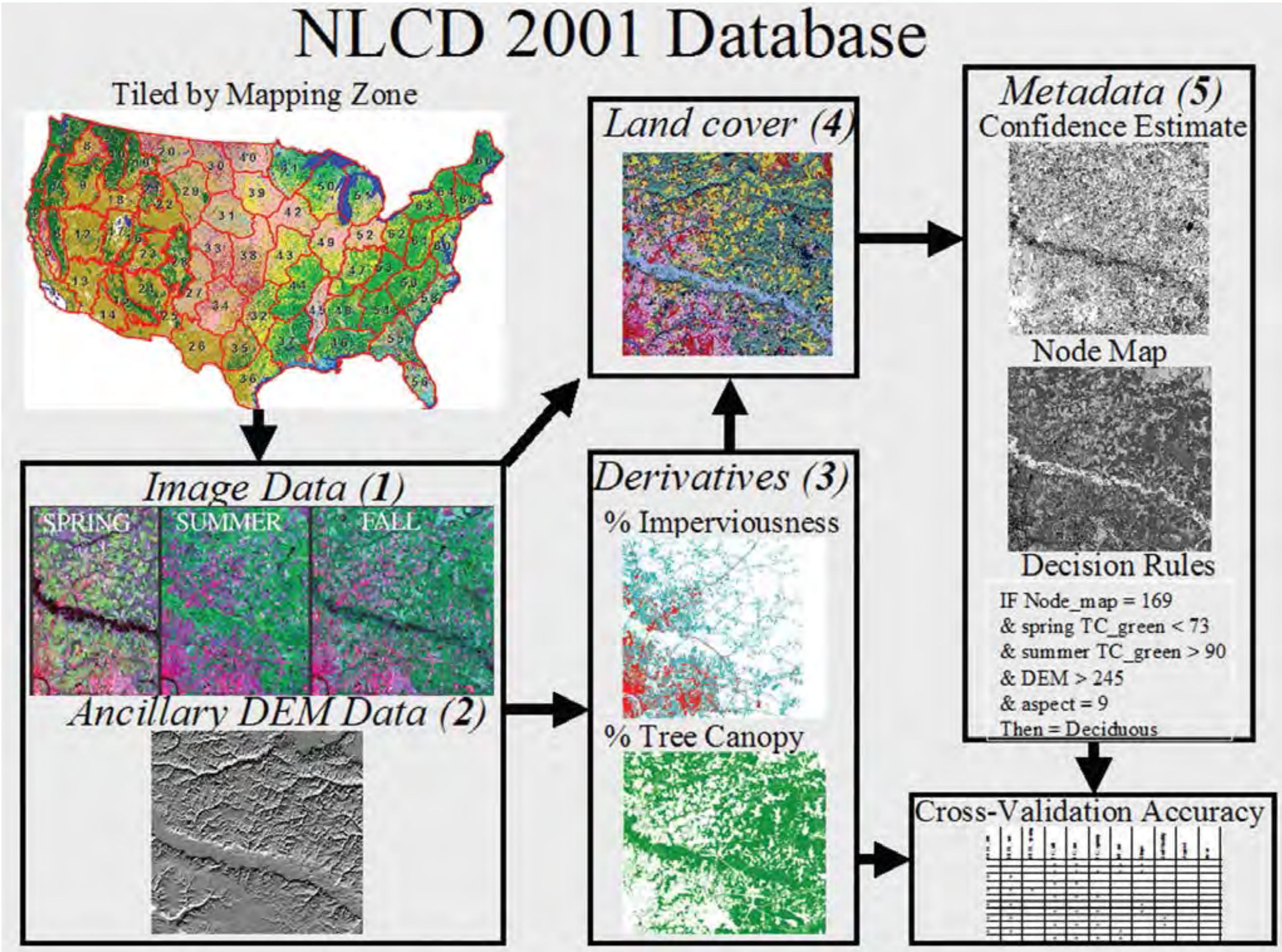
NLCD 2006

US National Land Cover Database (NLCD) - 2001



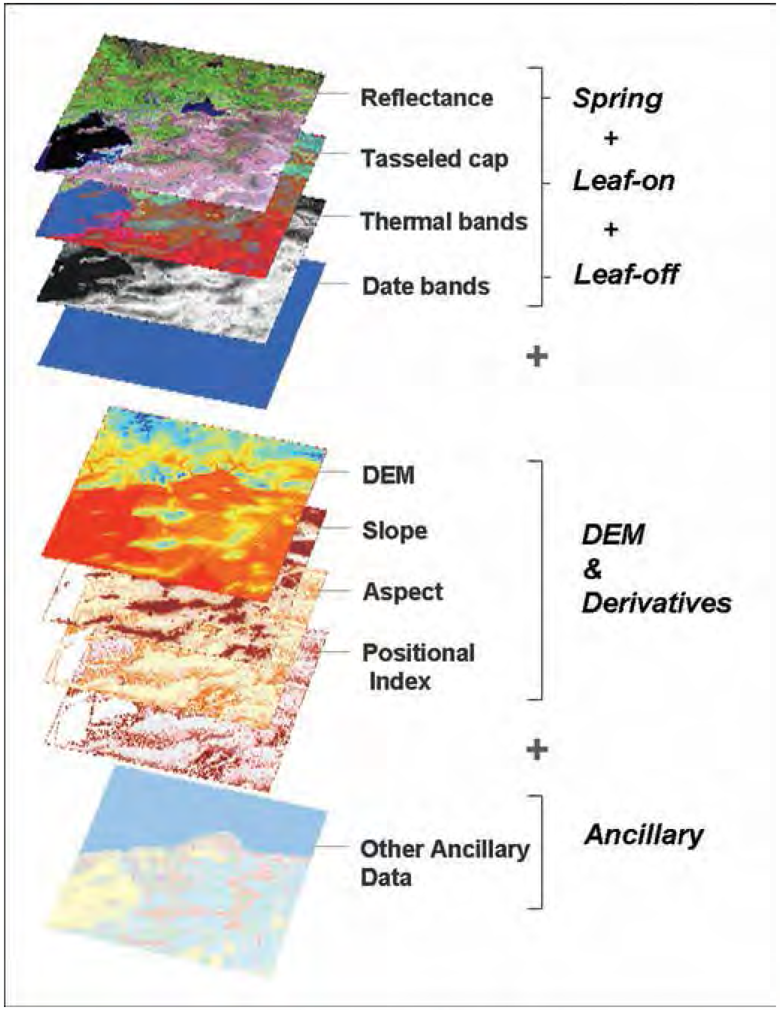
Source: Homer et al. (2007)

US National Land Cover Database (NLCD) - 2001

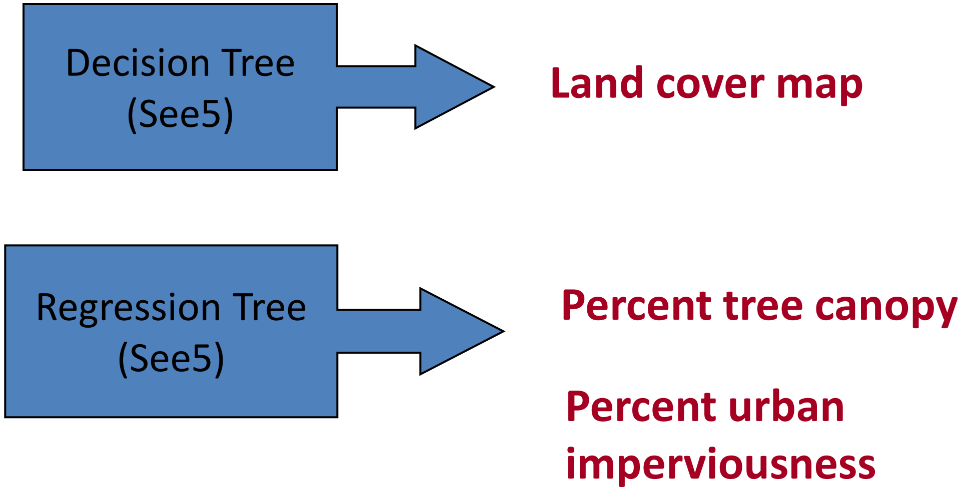


Source: Homer et al. (2004)

US National Land Cover Database (NLCD) - 2001



Mapping Zone Input Layers



Source: Homer et al. (2007)

Temporal consistency within NLCD maps

Land cover maps for 1992, 2001, 2006, 2011, …. (5 years periodicity)

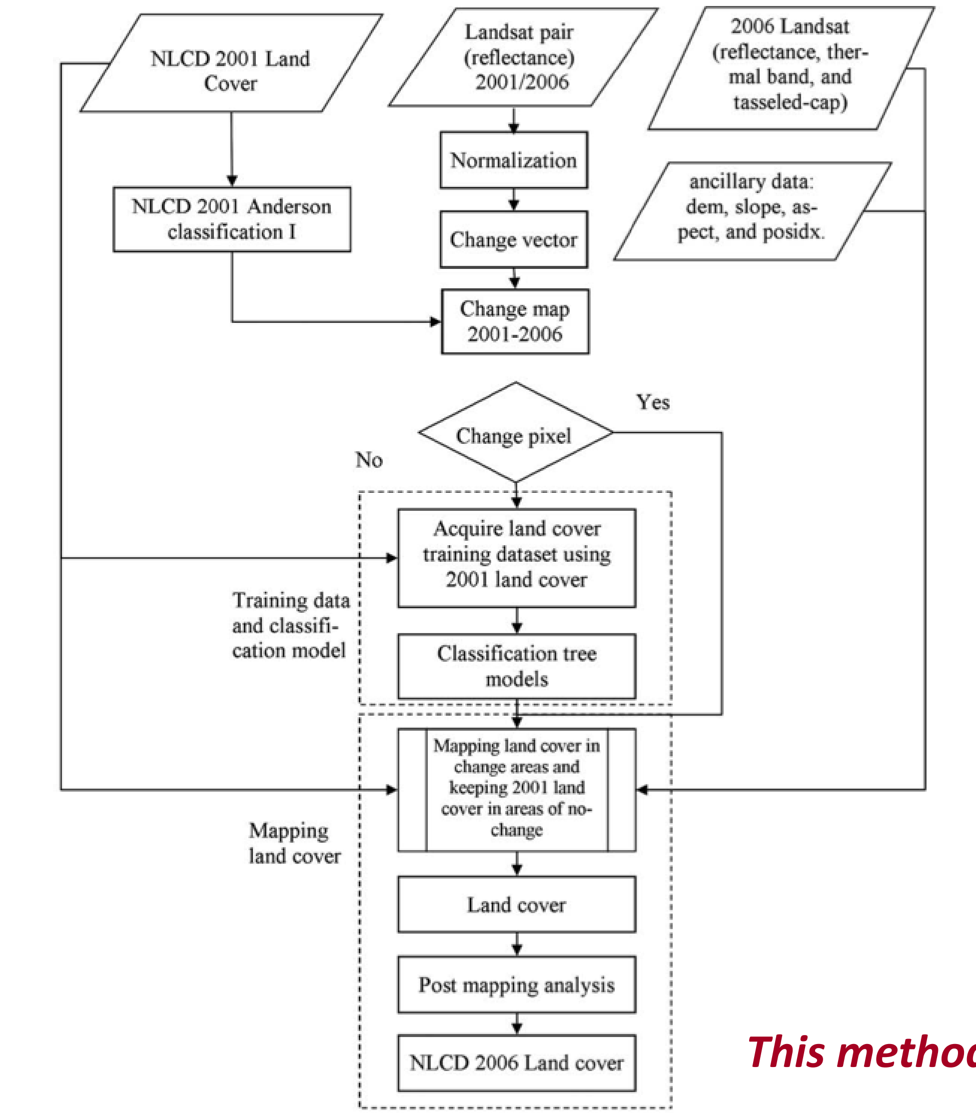
The current methodology

the production of 2011 will be based on the updating of the 2006 (like 2006 was based on 2001)

In the past

The original 2001 and 1992 NLCD were produced independently and with different methodologies.

Consequence: There is no temporal consistency and a direct comparison is meaningless



Production of NLCD2006

…or updating the NLCD2001 to 2006

The NLCD2006 is equal to the NLCD2001 except for the changed pixels.

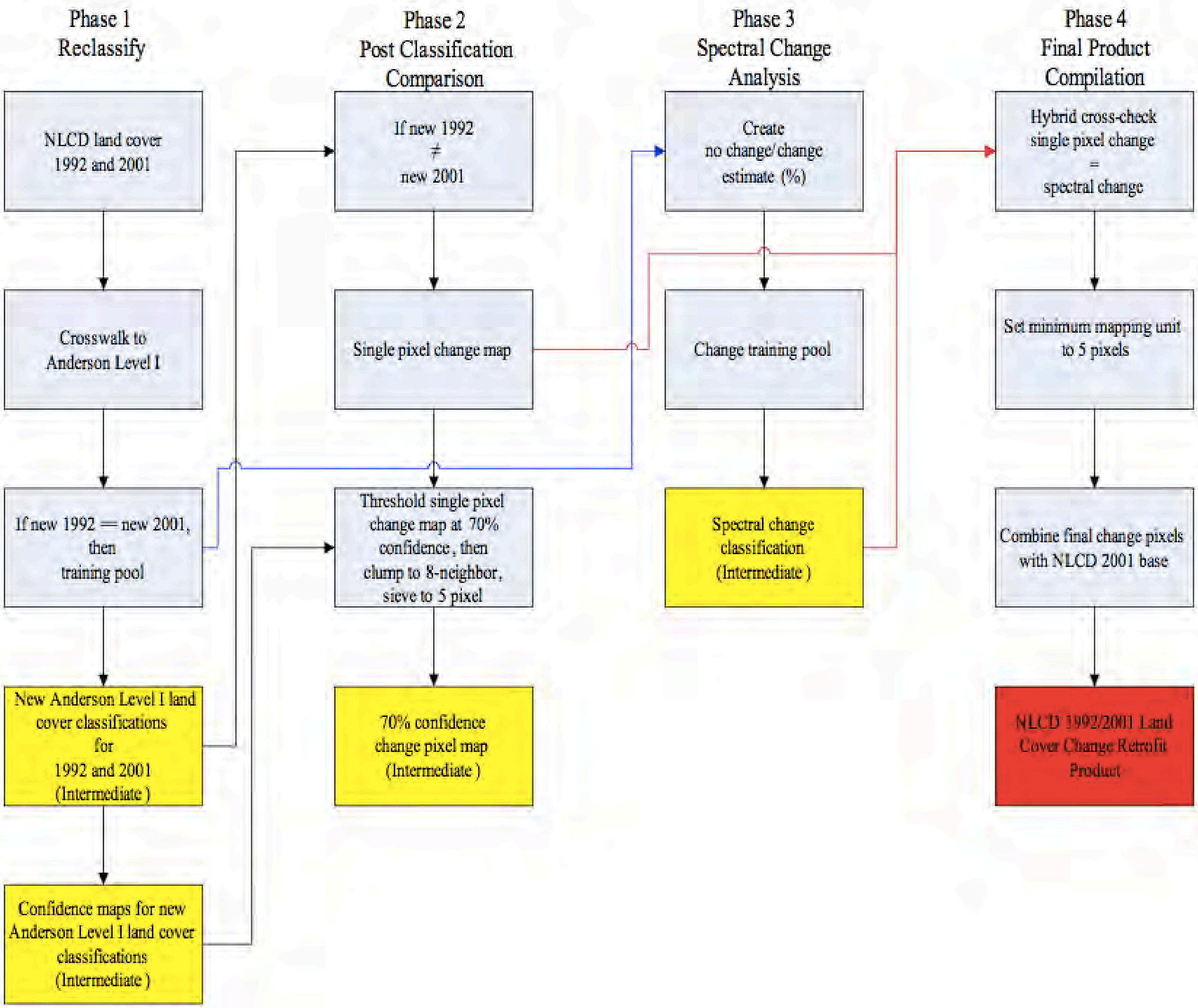
Images from 2001 and 2006 are first **normalised** to reduce radiometric differences introduced by atmosphere and sun geometry

The changed pixels are identified by **change vector analysis** driven by different thresholds based on land cover type (rather than a single threshold)

The changed pixels are classified by **decision tree classification** trained from the unchanged pixels.

This method guarantees the temporal consistency

Source: Xian et al., 2009



1992-2001
Land Cover Change Retrofit Product

The methodology incorporates both post-classification comparison and change detection based on the ratio image differencing

In unchanged areas the 1992 land cover class became the 2001 one (because NLCD2001 is more reliable)

Source: Fry et al., (2009)

Looking into the future – the production of NLCD2011

In NLCD2006 change detection was based on one image per year, which caused some commission errors.

NLCD2011 Two images per year to take into account the seasonal variability

Increasing availability of thematic ancillary data

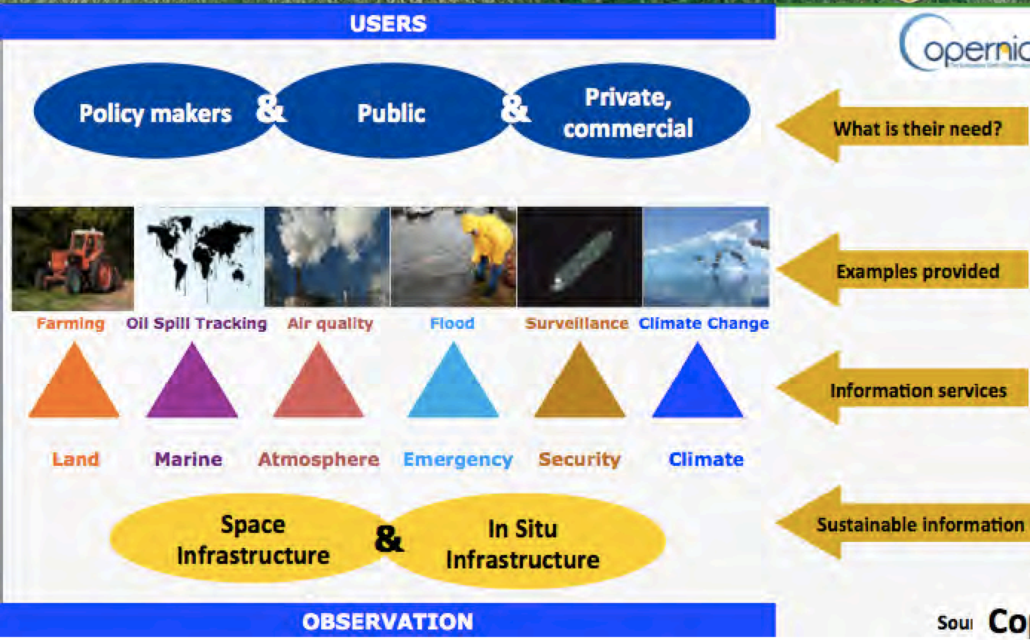
NLCD2011 Ancillary data includes:

- National Agriculture Statistical Service cropland data layers
(improve separation of cropland and pastures)
- National Wetland Inventory
(help the delineation of woody and herbaceous wetland classes
- NOAA Night time stable-light satellite imagery
(improve bare soil and urban areas discrimination)

Keep the 5 year production periodicity

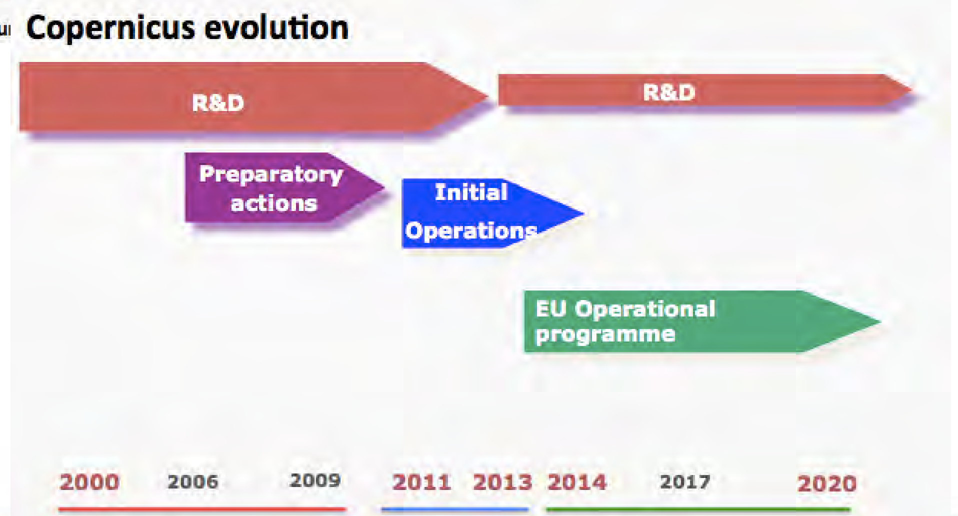
NLCD2011 Cost effective and fast way of map production
Compromise between accuracy and time and human resources

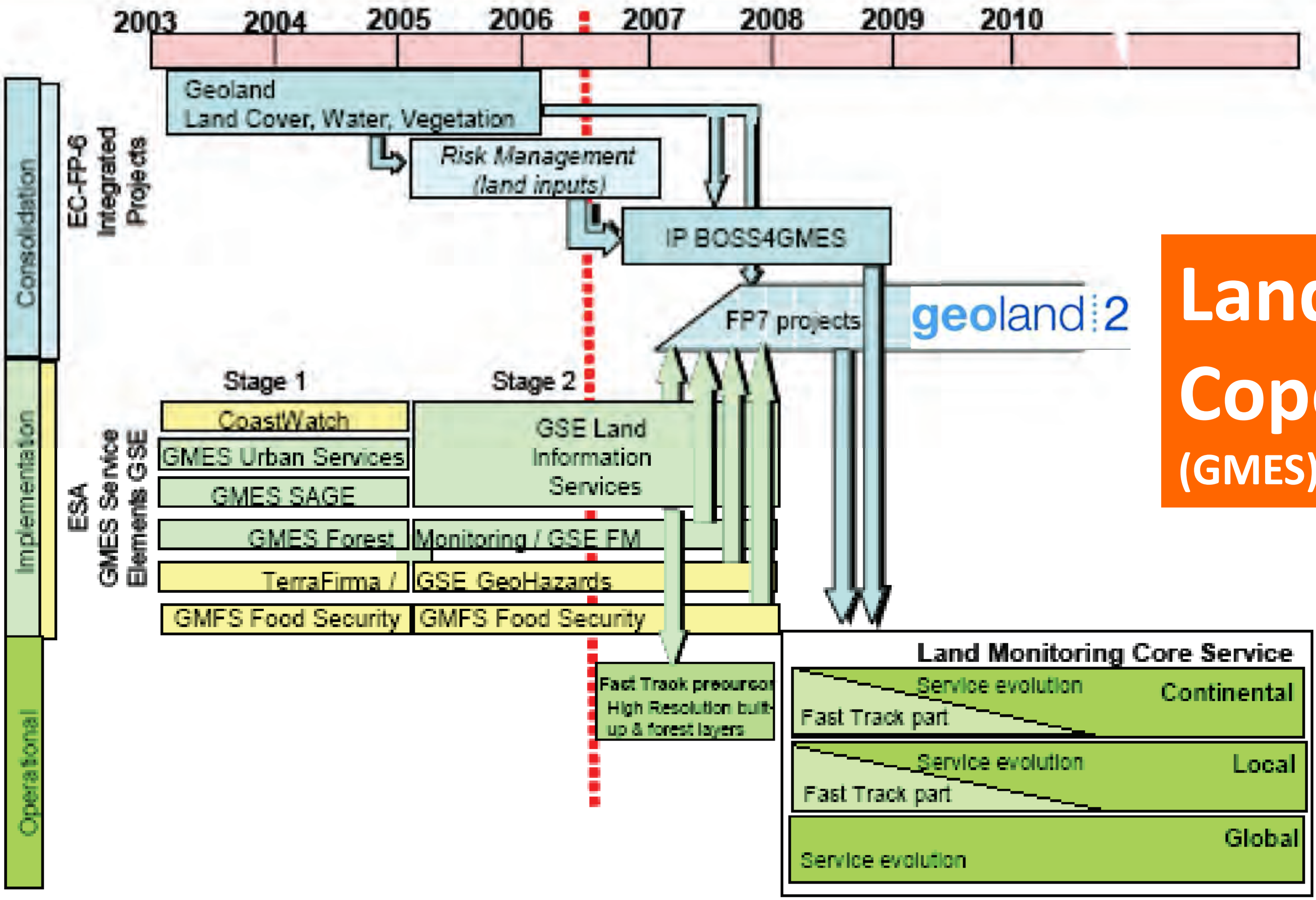
Source: Fry et al. (2011)



6 services

Land Monitoring Service





Land in Copernicus (GMES)

2011 - 2013

GMES Initial Operations

Source: IG-LMCS (2007)

http://www.gmes-geoland.info

Sept 2008

Dec 2012

Copernicus Land Monitoring Service – 3 components

Global

Bio-geophysical variables

- Fraction of vegetation cover
- Leaf Area Index
- NDVI
- Fraction of Absorbed Photosynthetically Active Radiation
- Albedo
- Surface Temperature

Pan-European

CORINE Land Cover

Five High Resolution Layers

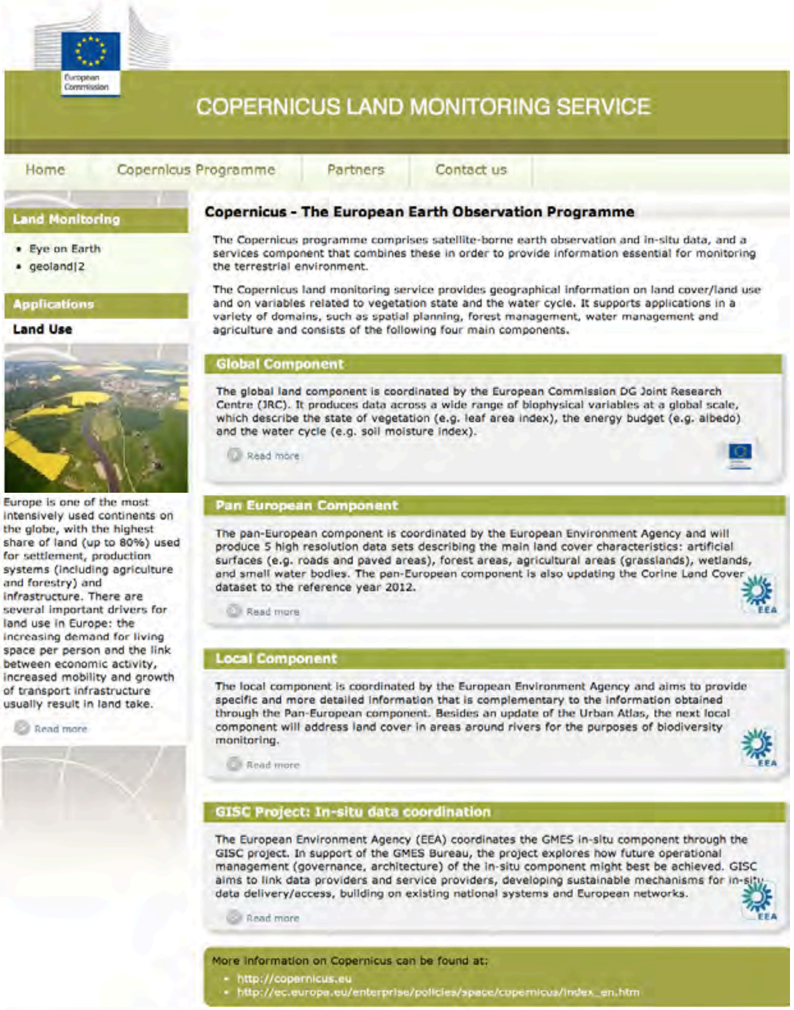
- Soil sealing
- Forest
- Grassland
- Wetland
- Water

Local

Urban Atlas

Riparian areas

Copernicus Land Monitoring Service – 3 components



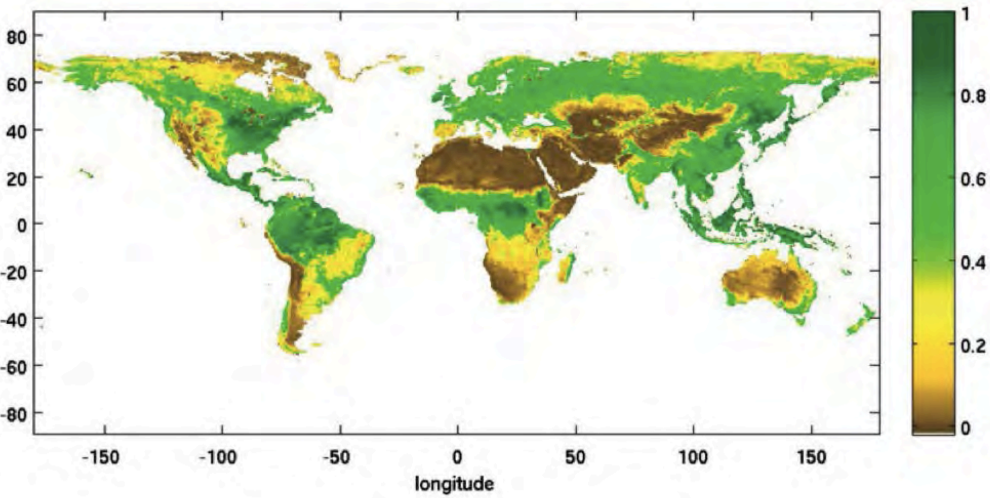
This service is more than LCLU or LCLUC. It also includes variables related to vegetation status and water cycle (i.e. biophysical variables).

http://land.copernicus.eu

Global

Bio-geophysical variables

- Fraction of vegetation cover
- Leaf Area Index
- NDVI
- Fraction of Absorbed Photosynthetically Active Radiation
- Albedo
- Surface Temperature



Fraction of vegetation cover

Dynamic land monitoring

1 day
10 days

Source: Jochum and Lacaze (2012)

Pan-European

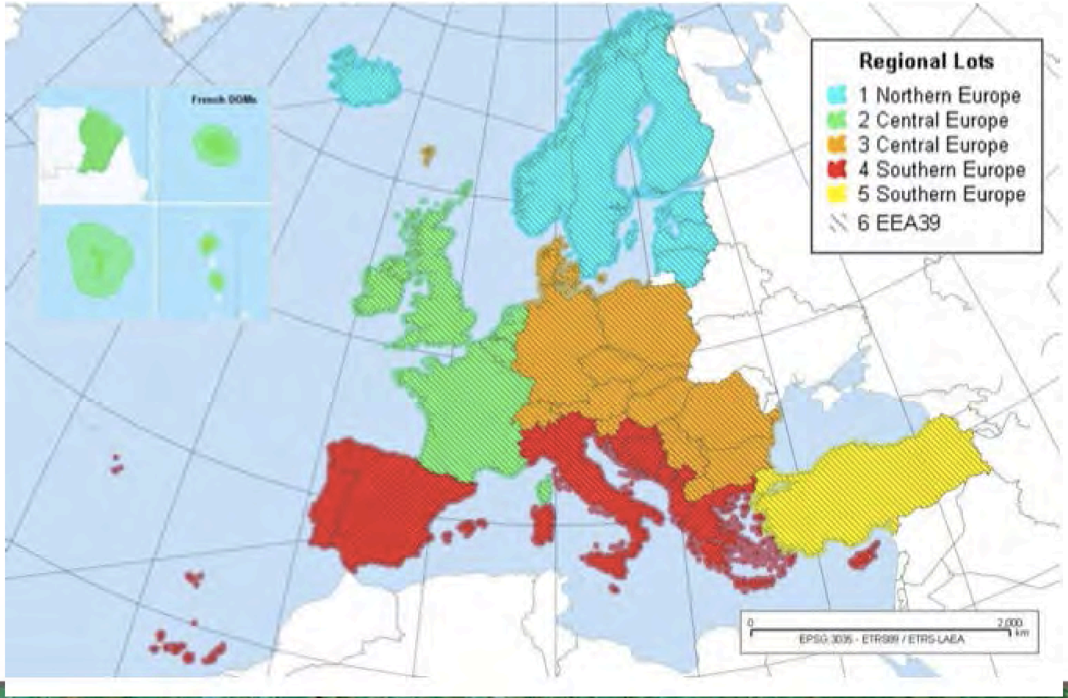
CORINE Land Cover

Five High Resolution Layers

- Soil sealing
- Forest
- Grassland
- Wetland
- Water

Five High Resolution Layers

Production by lot



Pan-European

Five High Resolution Layers

EEA 32 members + 7 cooperating countries

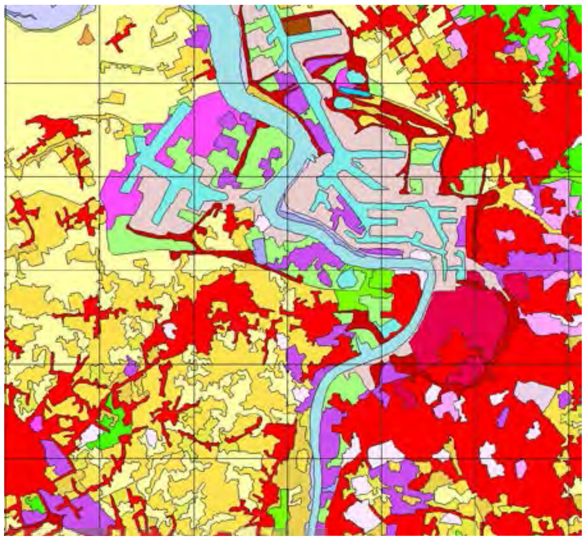
2012

Soil sealing	Degree of soil sealing (%) Soil sealing density change 2009 -2012	Also available 2006 and 2006-2009 change
Forest	Tree cover density (%, any type) Forest type (coniferous/deciduous, excludes trees under agriculture and urban use)	0.5 ha
Grassland	Presence of grassland (binary, any type) Occurrence of grassland (%) (excludes non-agriculture grassland)	
Wetland	Presence of wetlands (binay) Occurrence of wetlands (%)	Resolution: 20 m (non validated) 100 m (validated)
Water	Permanent water bodies (binary) Occurrence of permanent water bodies (%)	

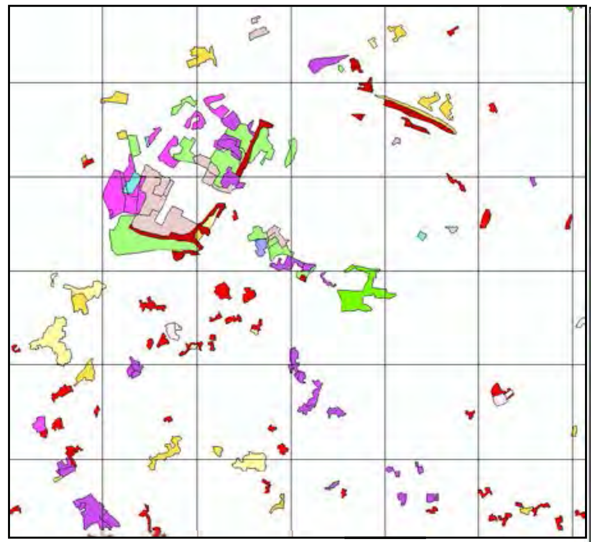
Pan-European

CORINE Land Cover 2012

EEA 32 members + 7 cooperating countries



CLC 2012



CLC Changes

Land cover classes

- Continuous urban fabric
- Discontinuous urban fabric
- Industrial or commercial units
- Road and rail networks and associated land
- Port areas
- Airports
- Mineral extraction sites
- Dump sites
- Construction sites
- Green urban areas
- Sport and leisure facilities
- Non-irrigated arable land
- Permanently irrigated land
- Rice fields
- Vineyards
- Fruit trees and berry plantations
- Olive groves
- Pastures
- Annual crops associated with permanent crops
- Complex cultivation patterns
- Land principally occupied by agriculture, with significant areas of natural vegetation
- Agro-forestry areas
- Broad-leaved forest
- Coniferous forest
- Mixed forest
- Natural grasslands
- Moors and heathland
- Sclerophyllous vegetation
- Transitional woodland-shrub
- Beaches, dunes, sands
- Bare rocks
- Sparsely vegetated areas
- Burnt areas
- Glaciers and perpetual snow
- Inland marshes
- Peat bogs
- Salt marshes
- Salines
- Intertidal flats
- Water courses
- Water bodies
- Coastal lagoons
- Estuaries
- Sea and ocean
- NODATA

Vector map
MMU 25 ha
44 classes

Vector map
MMU 5 ha
44 x 44 classes

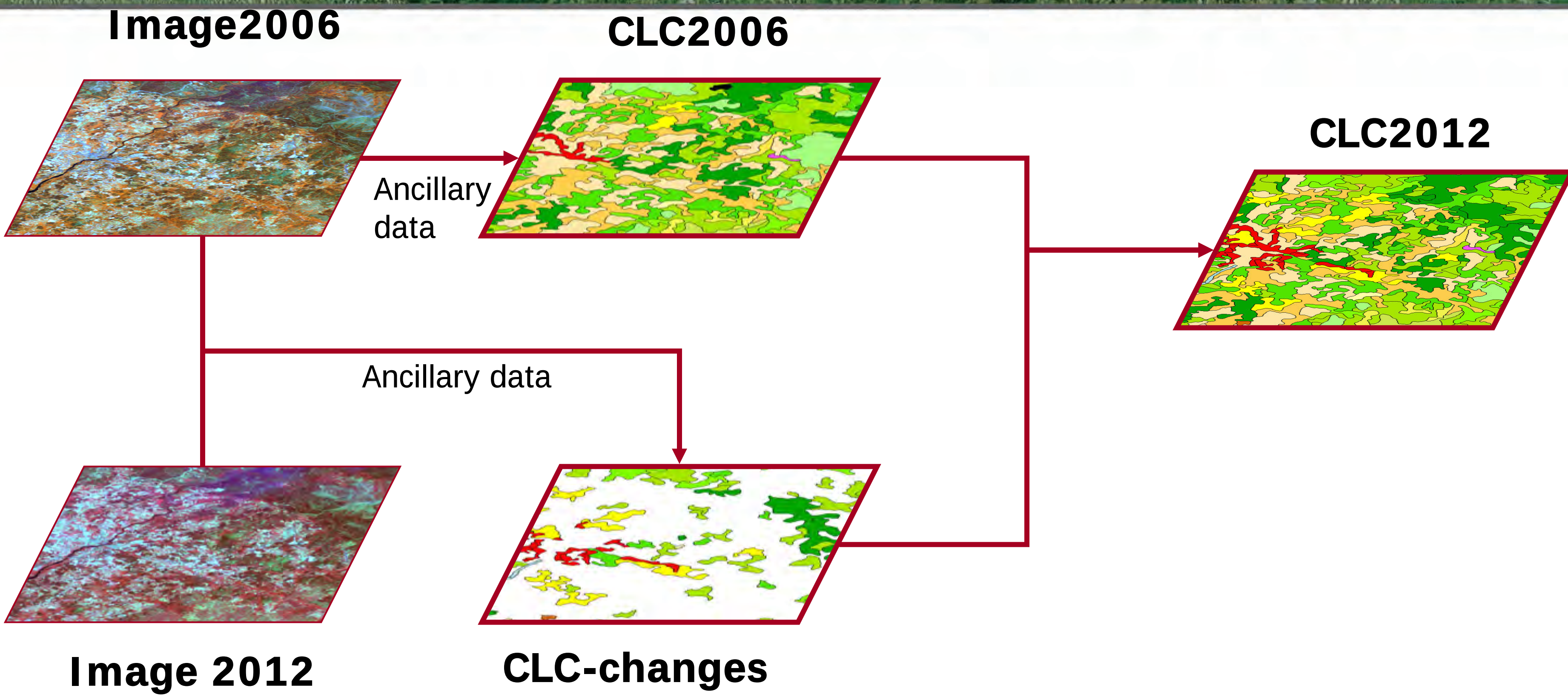
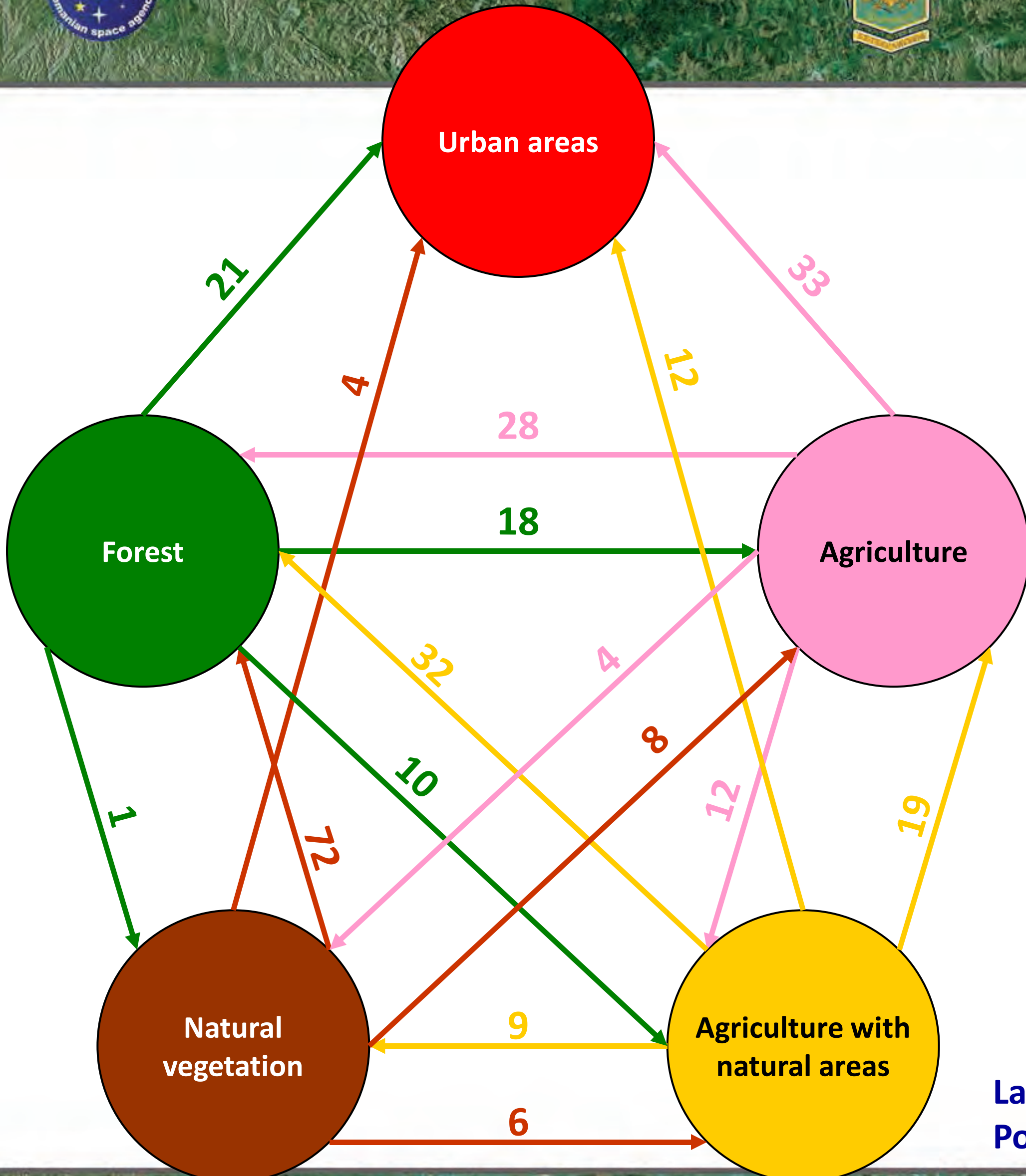
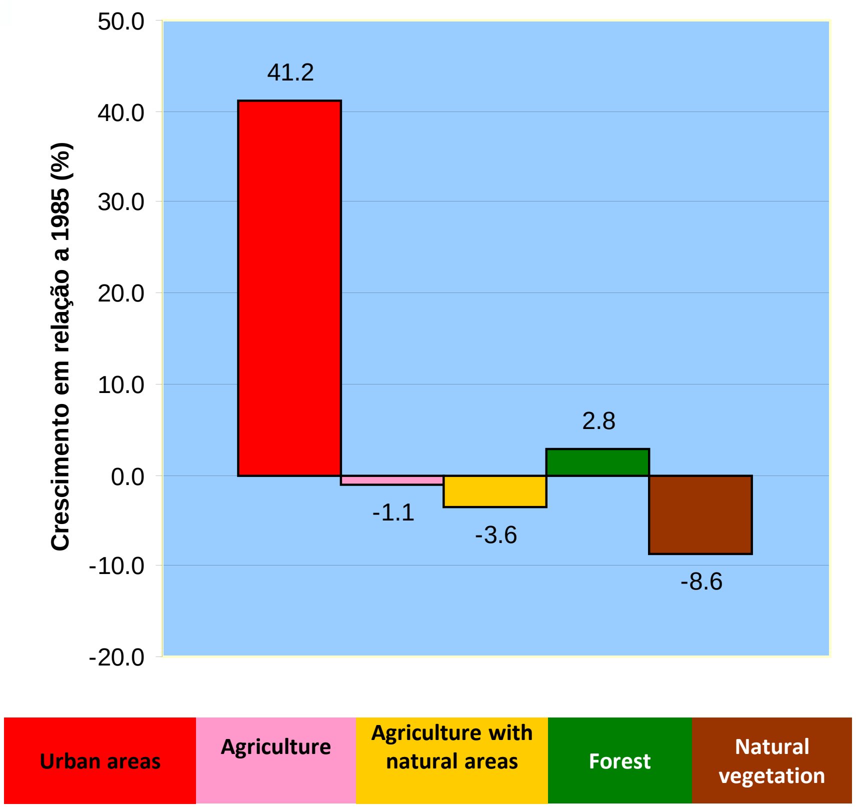


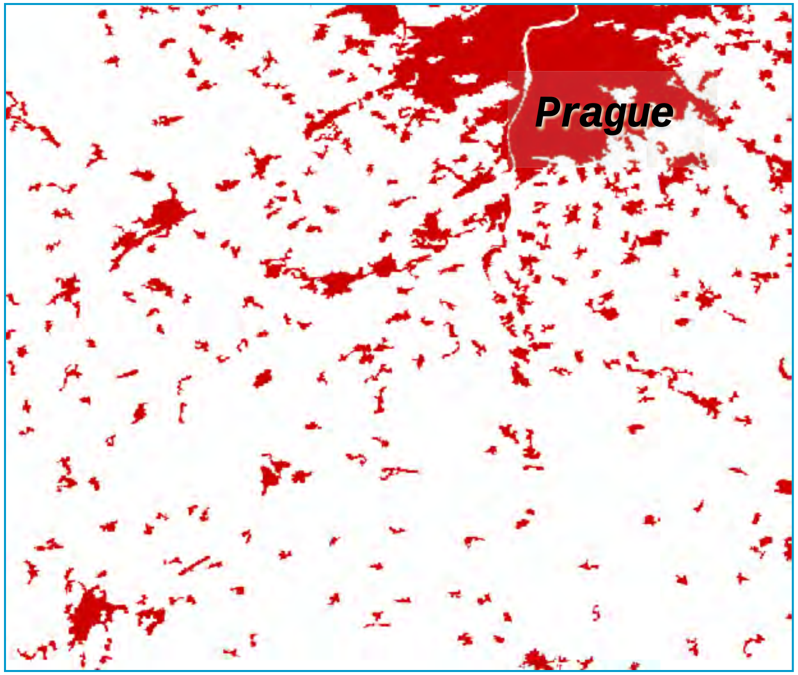
Image2006
CLC2006
CLC2012
Ancillary data
Ancillary data
Image 2012
CLC-changes





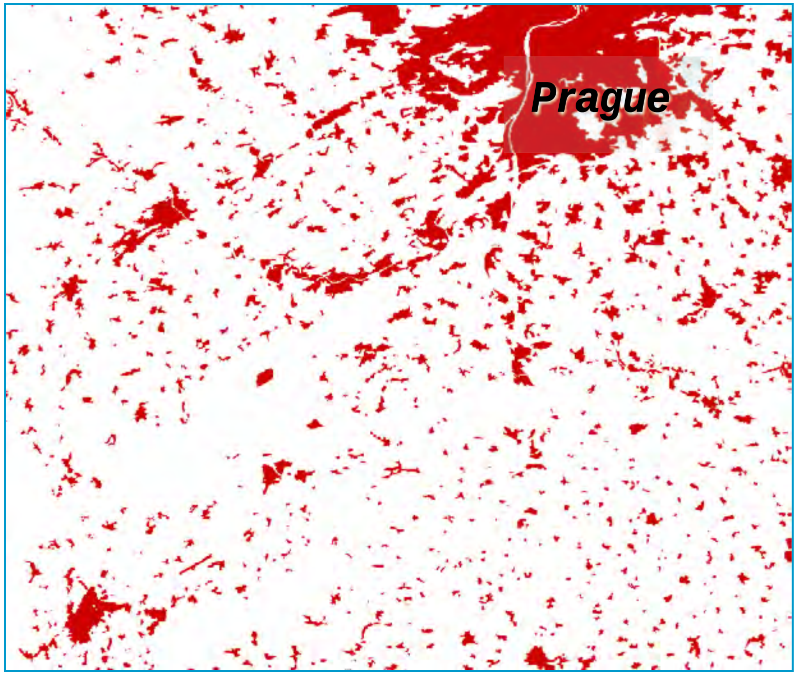
Land cover change from 1985 to 2000 in Portugal (thousands of ha)

CORINE Land Cover 2000 (100m grid)



Source: EEA

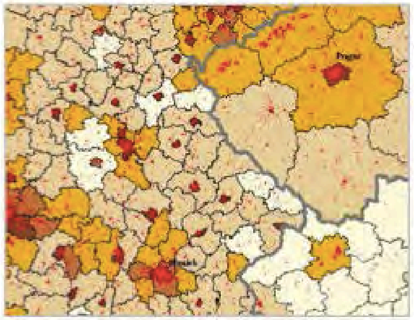
High-resolution layer for built-up areas 2000



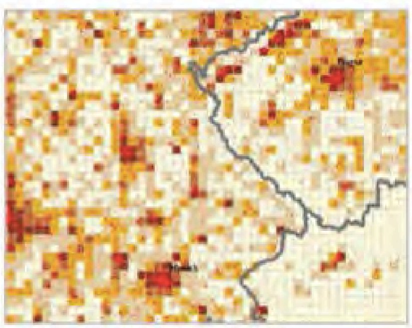
Source: GSE SAGE; Producer: GeoVille / GISAT

■	Artificial surfaces
□	Non-artificial surfaces

From lump statistics on administrative units

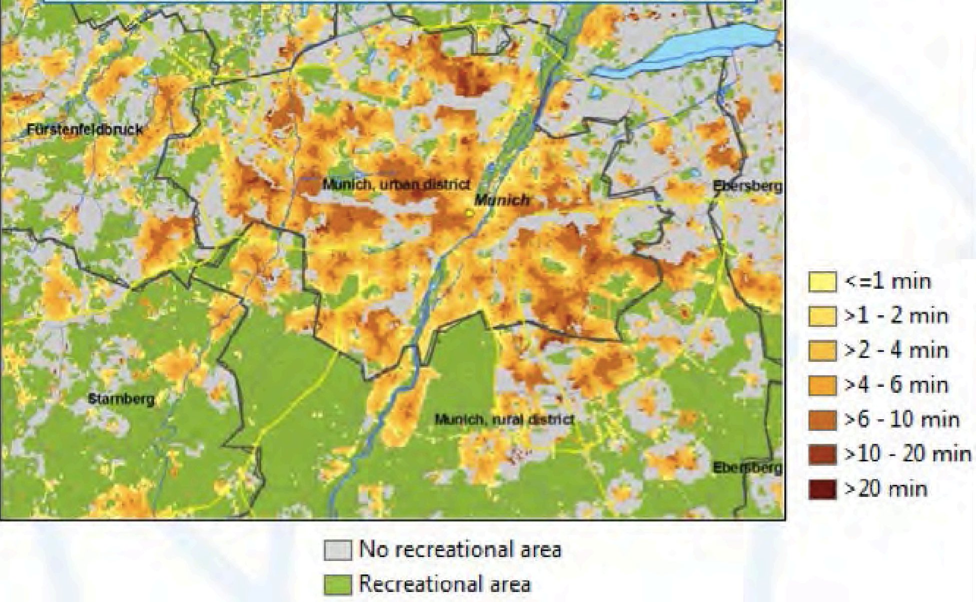


to geospatial explicit information (grid-based indicators)

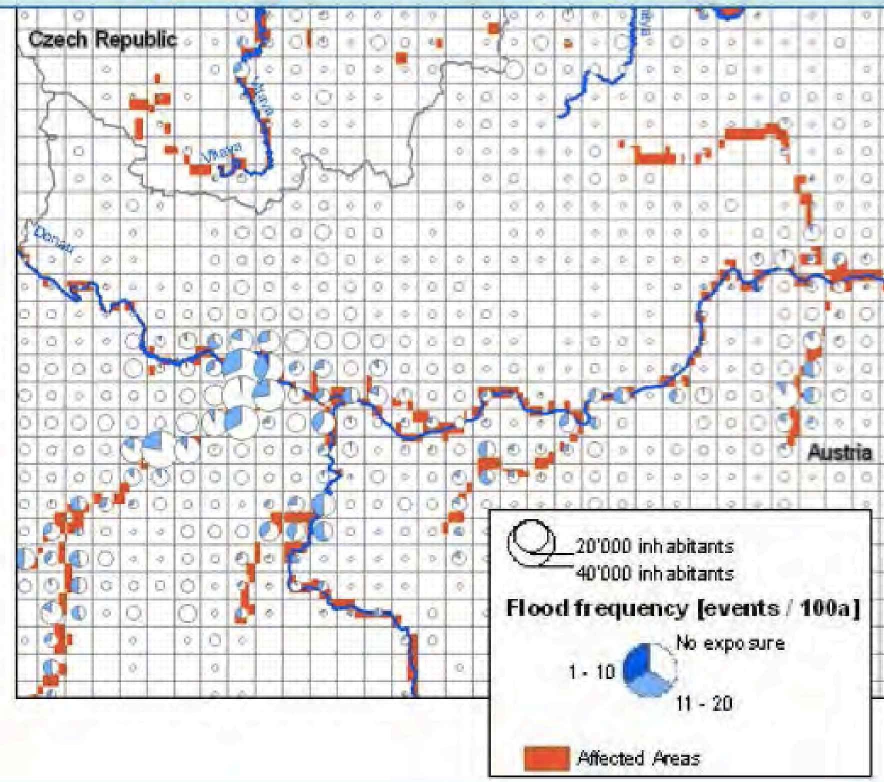


Source: Georgi and Hauffmann (2012)

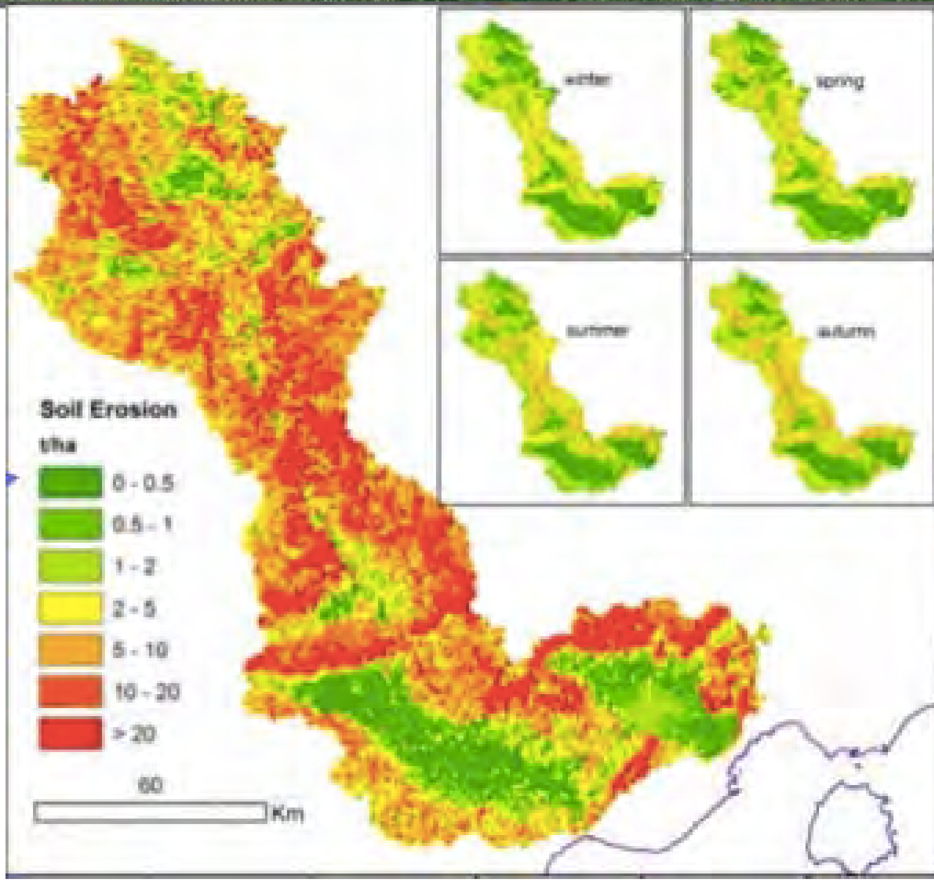
Travel time by car from residential areas to closest recreational zone



Population exposed to flood risk



Source: Georgi and Hauffmann (2012)



Soil sealing HR layer

↓

Soil erosion map

http://eusoils.jrc.ec.europa.eu/projects/Geoland2/data.html

Source: Jochum and Lacaze (2012)

Local

Urban Atlas

Riparian areas

Reference date: 2006

1:10 000

UMC (urban) – 0.25 ha

UMC (rural) – 1 ha

20 classes

LCLU maps for 305 European large urban areas (> 100 K habitants)

GIO Work Programme 2013 (under development)

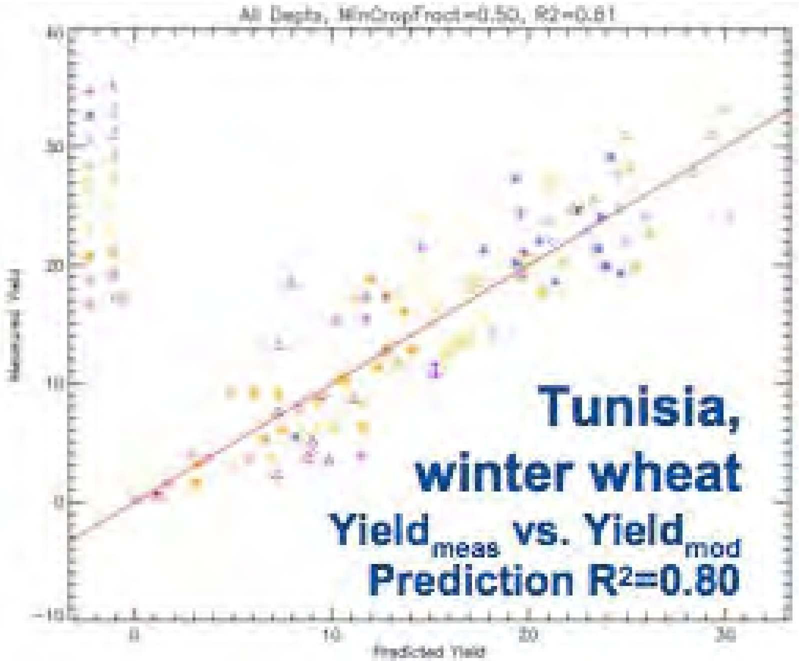
http://www.eea.europa.eu/data-and-maps/data/urban-atlas/

Source: Dufourmont (2012)

Crop Yield forecasts

Model crop growth to produce crop yield forecasts by combining biophysical products and agro-meteorological indicators

Bio-geophysical variables



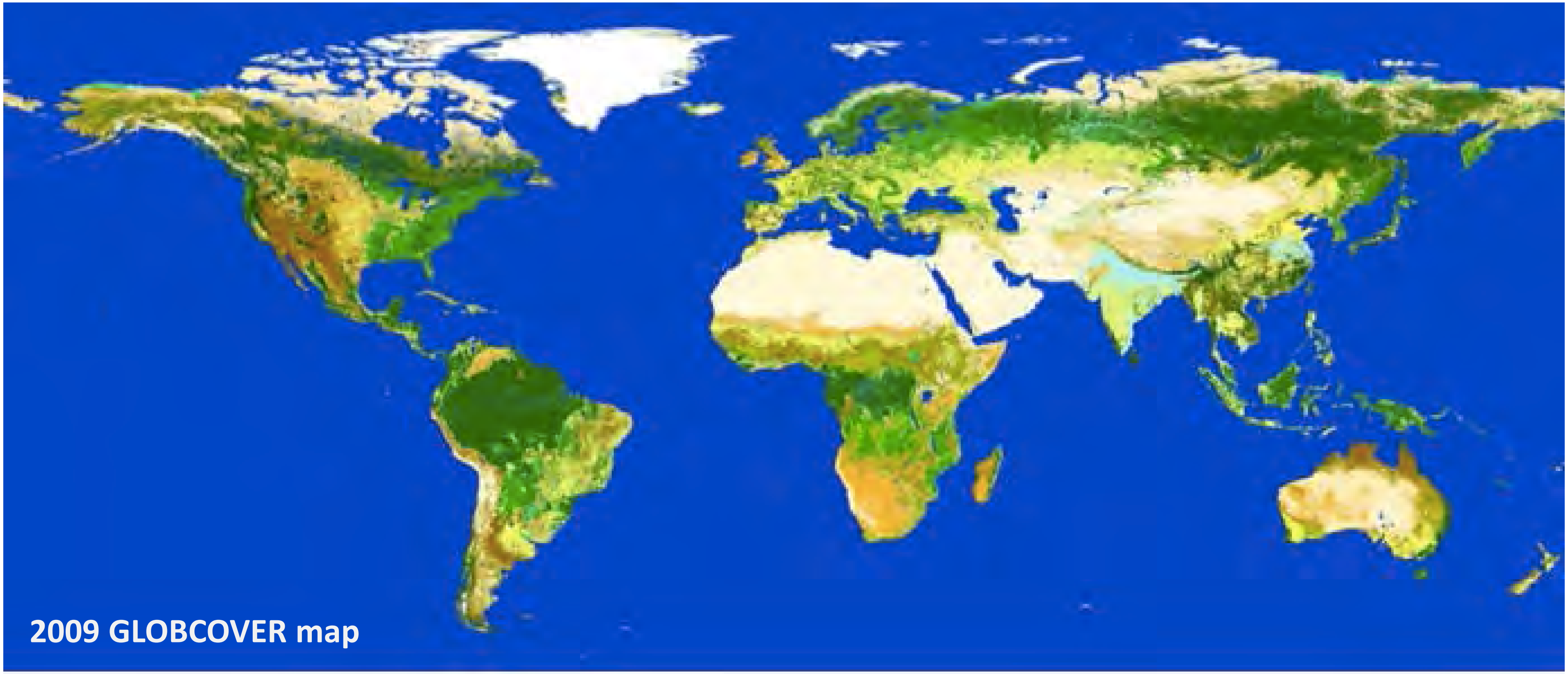
- Fraction of vegetation cover
- Leaf Area Index
- NDVI
- Fraction of Absorbed Photosynthetically Active Radiation
- Albedo
- Surface Temperature

Source: Jochum and Lacaze (2012)

Global land cover maps

	Images	Reference year	Spatial resolution	References
The 1st global LC map	AVHRR		1º	DeFries and Townshend (1994)
-	AVHRR		8 km	DeFries et al. (1998)
-	AVHRR		1 km	Loveland et al. (2000)
MODIS LC map (MOD12Q1)	MODIS	2001	1 km	Friedl et al. (2002)
Global Land Cover 2000 (GLC2000)	VEGETATION	2000	1 km	Bartholomé and Belward (2005)
GLOBCOVER	MERIS	2005 2009	300 m	Arino et al. (2007) Bontemps et al. (2011)
GLOBCOVER	Landsat	2000 2010	From 30 m to 300m (depends on class)	Chen et al. (2015)

GLOBCOVER



The GLOBCOVER collaboration

esa | GOFC-GOLD | GLOBAL CHANGE | GTOS | FAO | UNEP | EUROPEAN COMMISSION DIRECTORATE GENERAL Joint Research Centre

http://due.esrin.esa.int/globcover/

GLOBCOVER

GLOBCOVER is intended to improve previous global products, in particular through a finer resolution (300m) and a 22 classes nomenclature.

GLOBCOVER2005 and GLOBCOVER2009 were produced independently but with the same methodology

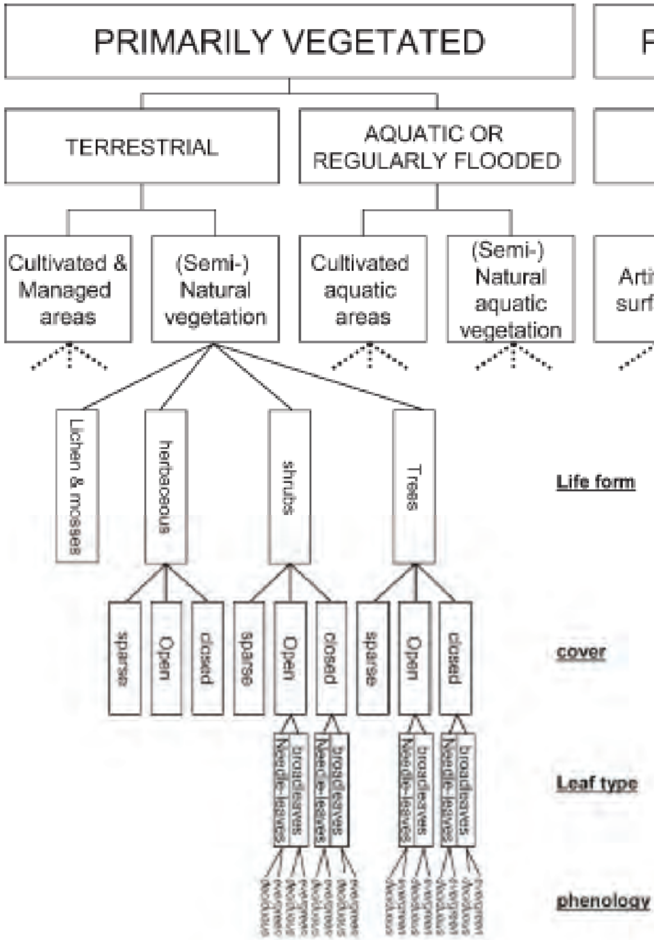
Production times:
GLOBCOVER 2005 – from 2005 till 2008
GLOBCOVER 2009 – 2010

Large volumes of data
e.g. GLOBCOVER 2009 - 20 TB of images acquired in 2009

GLOBCOVEE 2005 – produced by a consortium coordinated by MERIA FR
GLOBCOVER 2009 – produced by ESA and Université Catholique de Louvain

Source: Defourny et al. (2005); Arino et al. (2009; Bontemps et al. (2011)

GLOBCOVER



Hierarchical tree from LCCS

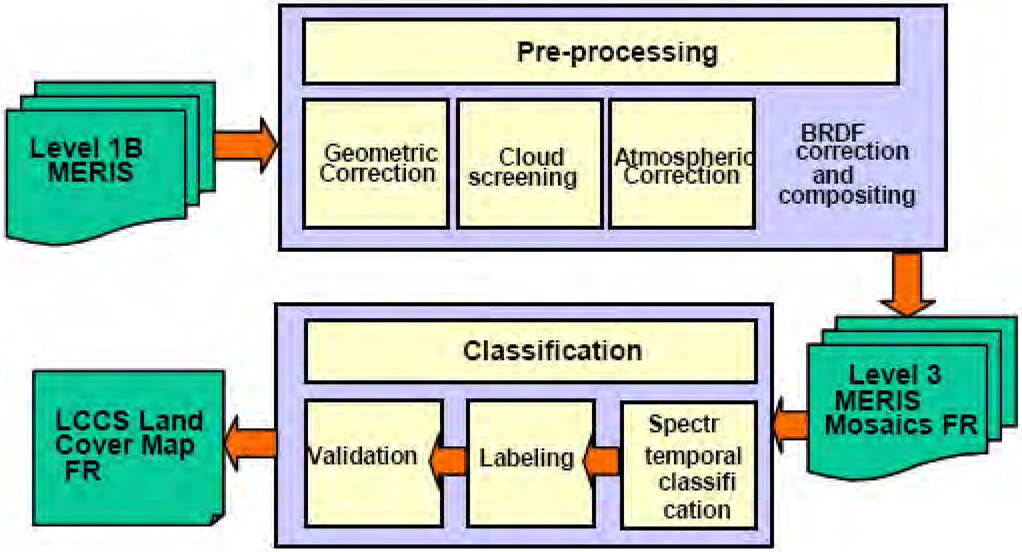
The nomenclature of GLOBCOVER is based on the Land Cover Classification System (LCCS) from FAO

Global product – 22 land cover classes

Source: Bartholomé and Belward (2005)

GLOBCOVER

The GLOBCOVER system

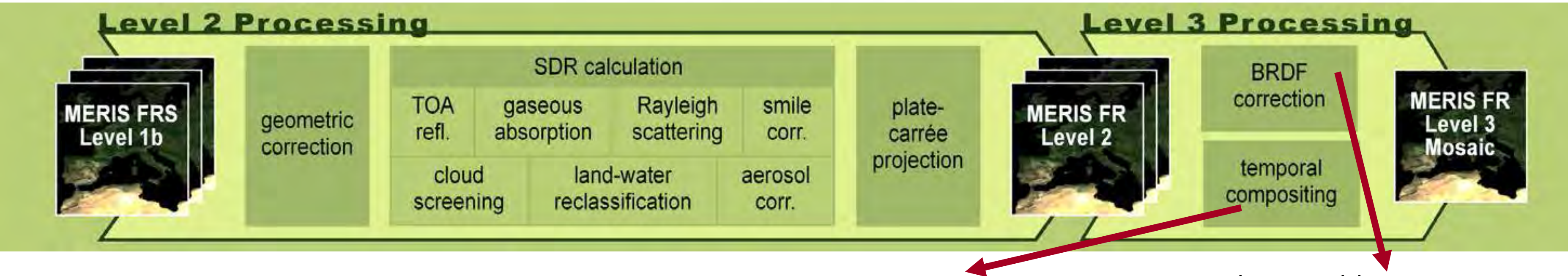


GLOBCOVER 2005 developed an operational service for global land cover mapping based on an automated processing chain.

GLOBCOVER 2005 demonstrated the capacity to produce global land cover maps on an yearly basis and with a satisfactory accuracy

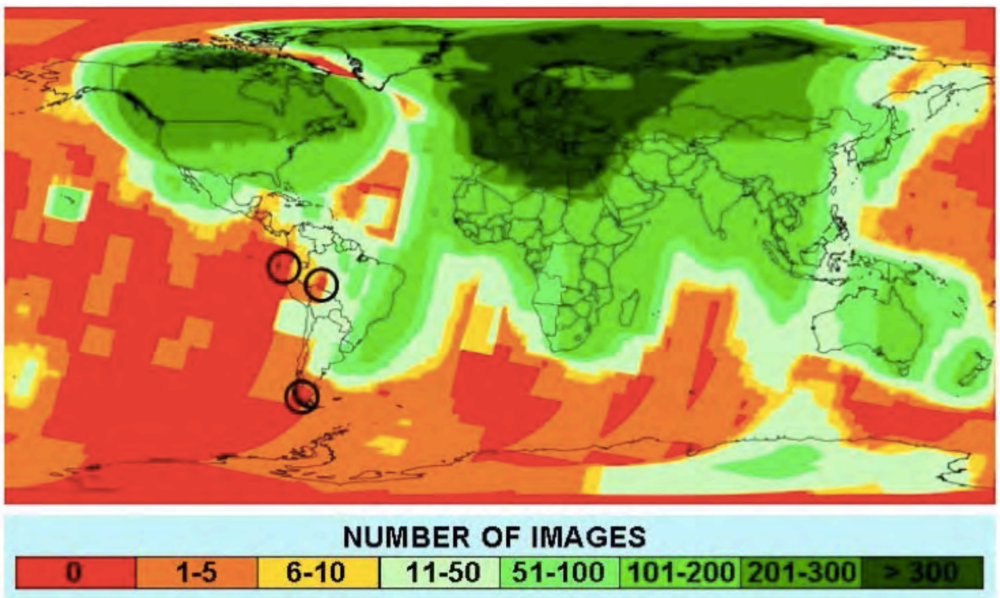
Source: Defourny et al. (2005); Bontemps et al. (2011)

Surface reflectance mosaics generation



bi-monthly mosaics

Temporal compositing generates seasonal and annual mosaics by averaging the monthly mosaics over the selected period.



Geometric correction – ARGOS (ESA software) 2009 – RMS 77 m

Radiometric correction – conversion of top-atmosphere-reflectance into ground reflectance (

Images were subset into 5º by 5º tiles

Cartographic projection - Plate-Carrée (WGS84 ellipsoid).

Source: Arino et al. (2007); Bontemps et al. (2011)

GLOBCOVER

Stratification into equal-reasoning areas

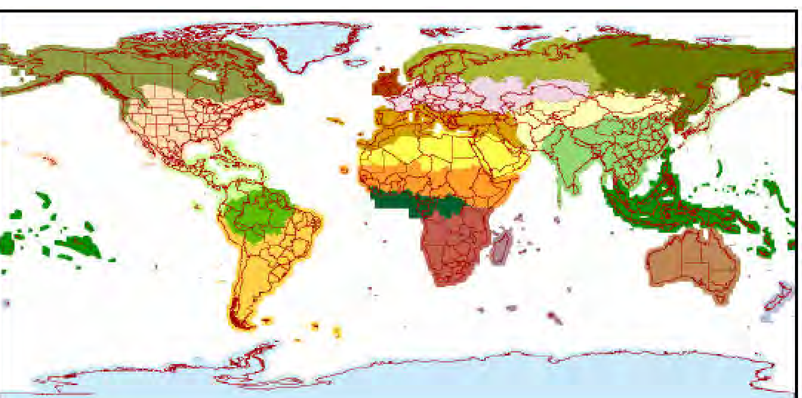
It reduces the land cover variability

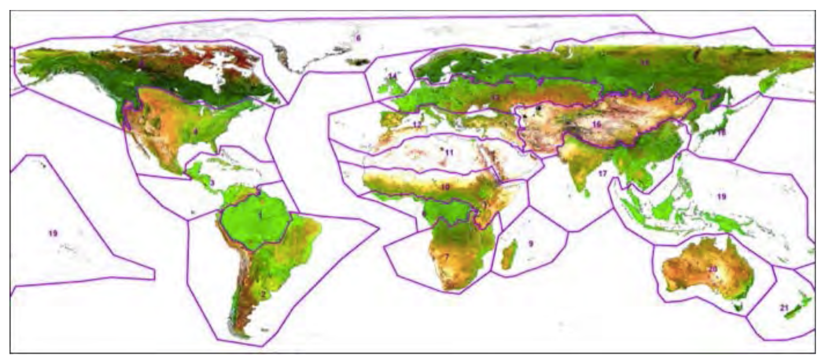
Allows selection of region specific classification parameters (e.g., temporal synthesis, band combinations, number of classes)

To improve discrimination efficiency of the classification algorithms

Criteria

- vegetation seasonality
- cloud coverage
- sun zenith angle
- data availability
- burning period
- snow cover



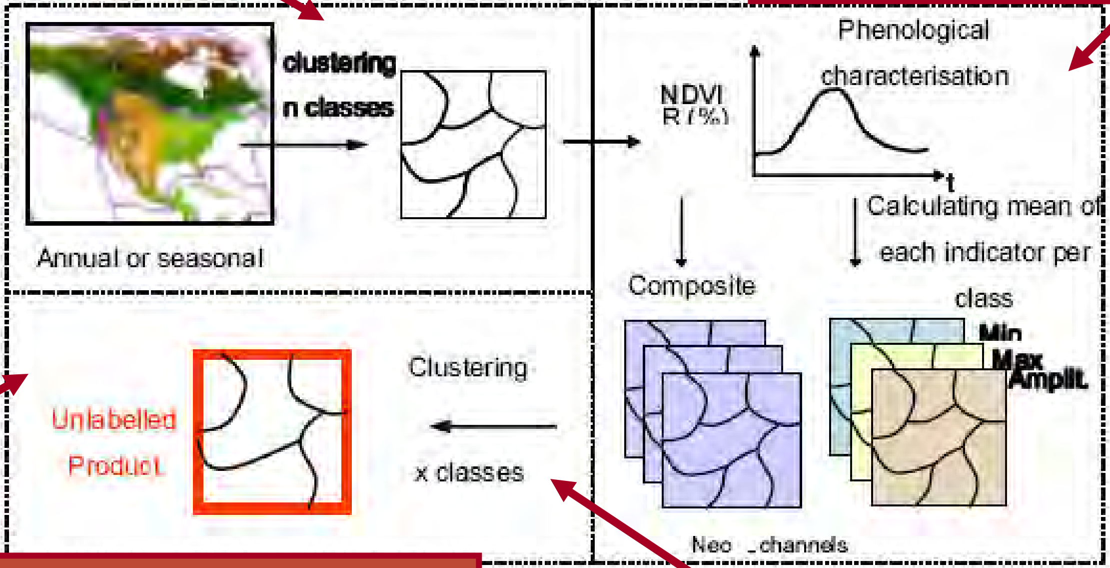


Source: Defourny et al. (2005); Bontemps et al. (2011)

GLOBCOVER

Step 1 (per-pixel classification)
Definition of homogenous land cover objects

Step 2 (per-cluster characterisation)
Derivation of neo-channels based on phenological metrics
(min and max of vegetaiton for each cluster)



Step 4
Clusters labeling using LCCS
(in 2009 a labelling-rule based procedure using GLOBCOVER 2005 was used)

Step 3 (per-cluster classification)
LC discrimination through iterative multidimensional clustering techniques
(spectro-temporal classes)

Source: Defourny et al. (2005); Bontemps et al. (2011)

GLOBCOVER 2005 and 2009

Accuracy assessment*

GLOBCOVER 2005	79.3%	Defourny et al. (2009)
GLOBCOVER 2009	70.7%	Bontemps et al. (2011)

The reference land cover used in cluster labelling is of paramount important

The accuracy depends on the number of images available for each pixel
(e.g. low accuracy in some Amazonia and northern regions)

The use of ancillary data improved significantly the accuracy of the maps
(e.g., 2000 Water Body Data from the Shuttle Radar Topography Mission (SRTM) for water bodies)

The lack of short wave infrared bands contributes to misclassification in tropical forests

The land cover nomenclature contains too many mosaic classes wit decreases thematic detail

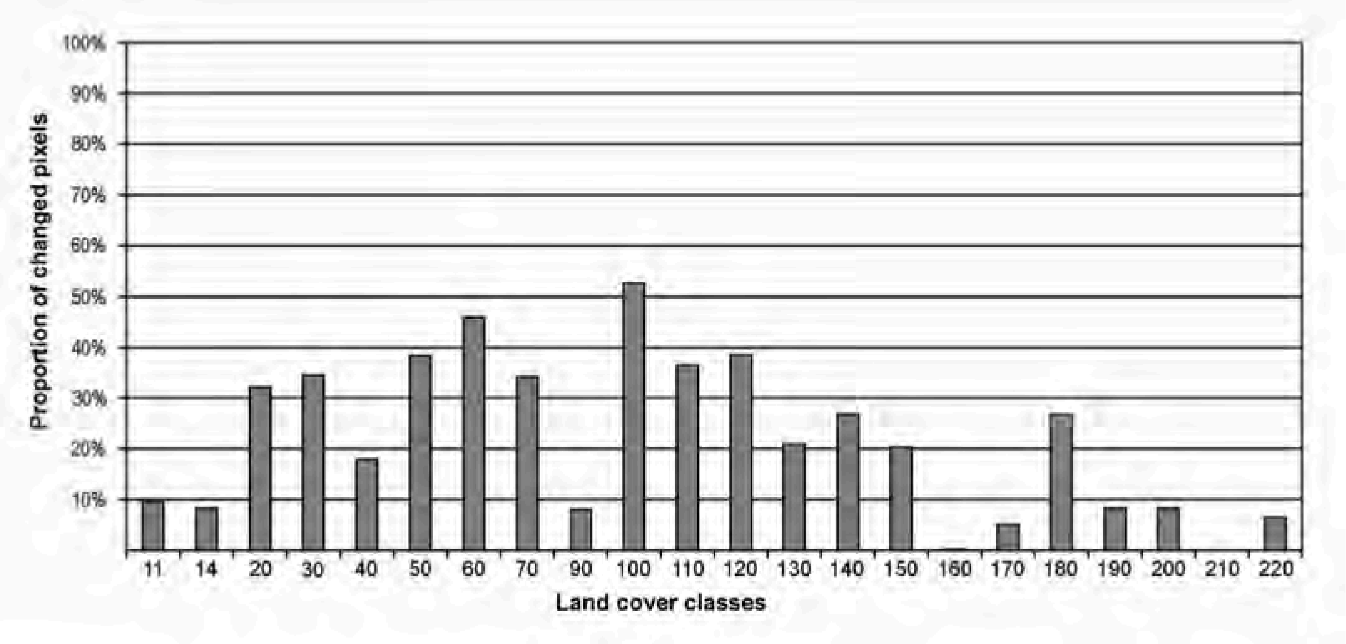
The map accuracy is region dependent

*** Considering "certain (no doubt) and homogenous (one class) pixels" and not weighted by class area**

GLOBCOVER 2005 and 2009 — Comparison or land cover change?

"Pixels that are differently classified in the GlobCover 2005 and 2009 land cover maps are too numerous to be representative only for land cover changes.

They should rather be interpreted like classification instabilities."



There is a temporal inconsistency and therefore land cover change studies are not possible

Source: Bontemps et al. (2011)

Summary

1 Setting the scene

2 The need for LULC monitoring data

- LCLU: a cross-cutting environmental variable
- LCLU monitoring and environmental legislation
- Relation between two European initiatives (Copernicus and INSPIRE) and LCLU monitoring
- Hard and soft LCLU maps
- The Land Cover Classification System

3 From data to information: some important advances in LCLU monitoring

- Two different approaches for LCLU monitoring
- Spectral and class change detection
- Image classification for LCLU mapping

4 LCLU monitoring operational programs

- At country level (NLCD from USA)
- At European level (Land monitoring service within Copernicus)
- At Global level (GLOBCOVER)

2014

A new era is starting

2000 to 2013
3.2 b€

Funding

2014 to 2020
3.8 b€

Growing availability of different types of images (the era of the multi-)

Specific missions

L2andL3 products

Free access data policy

New paradigma in Earth observation

New methodologies

New products

References

Anderson, J., E. Hardy, J. Roach, and R. Witmer, 1976. A land use and land cover classification system for use with remote sensor data. U.S. Geological Survey Professional Paper 964.

Arino, O. et al., 2007. GlobCover: ESA service for Global Land Cover from MERIS. Proceedings of IGARSS' 2007, Barcelona (Spain), 23-27 July, 2007.

Atkinson, P.M., 2004. Resolution manipulation and sub-pixel mapping, in S.M. de Jong and F.D. van der Meer (eds), Remote sensing image analysis – including the spatial domain, Dordrecht: Kluwer Academic Publishers.

Bartholomé, E., and Belward, 2005. GLC2000: a new approach to global land cover mapping from Earth observation data. International Journal of Remote Sensing, 26(9): 1959-1977.

Bartholomé, E., A. Belward, F. Achard, S. Bartalev, C. Carmona-Moreno , H. Eva, S. Fritz, S., J-M Grégoire, P. Mayaux, and H.-J. Stibig, 2002. GLC2000—Global Land Cover Mapping for the Year 2000—project Status November 2002. Publications of the European Commission, EUR 20524 EN (Luxembourg: Office for Official Publications of the European Communities).

Bontemps, S., P. Defourny, E. Bogaert, O. Arino, V. Kalogirou and J. Perez, 2011. Products Description and Validation Report.

Bossard, M., J. Feranec and J. Otahel, 2000. CORINE Land Cover Technical Guide – Addendum 2000. Technical report No 40, Copenhagen (EEA).

Boyd, D., and G. Foody, 2011. An overview of recent remote sensing and GIS based research in Ecological Informatics. Ecological Informatics, 6: 25-36.

Chen, J., J. Chenb, A. Liaoa, X.Caob, L. Chena, X.Chenb, C. Hea, G.Hana, S.Penga, M.Lua, W.Zhanga, X.Tongc, and J. Millsdet al., 2015. Global land cover mapping at 30 m resolution: A POK-based operational approach, ISPRS Journal of Photogrammetry and Remote Sensing, 103: 7 – 27.

Defourny, P., Schouten, L., Bartalev, S., Bontemps, S., Caccetta, P., de Witt, A., di Bella, C., Gerard, B., Giri, C., Gond, V., Hazeu, G., Heinimann, A., Herold, M., Jaffrain, G., Latifovic, R., Ling, H., Mayaux, P., Muncher, S., Nonguierma, A., Stibig, H-J., Van Bogaert, E., Vancutsem, C., Bicheron, P., Leroy, M. and Arino, O., 2009. Accuracy Assessment of a 300-m Global Land Cover Map: the GlobCover Experience, Proceedings of the 33rd International Symposium on Remote Sensing of Environment (ISRSE), Stresa, Italy, May 2009.

Defourny, P., Vancutsem, C., Bicheron, P, Brockmann, C., Nino, F., Schouten, L., Leroy, M., 2006. GLOBCOVER: a 300m global land cover product for 2005 using ENVISAT MERIS Time Series, Proceedings of ISPRS Commission VII Mid-Term Symposium: Remote Sensing: from Pixels to Processes, Enschede (NL), 8-11 May, 2006.

DeFries, R., Hansen, M., Townsend, J. G. R., and Sohlberg, R., 1998. Global land cover classifications at 8 km resolution: the use of training data derived from Landsat imagery in decision tree classifiers. International Journal of Remote Sensing, 19: 3141– 3168.

DeFries, R. S., & Townshend, J. G. R., 1994. NDVI derived land cover classifications at a global scale. International Journal of Remote Sensing, 5: 3567– 3586.

Di Gregorio, A., 2005. UN Land Cover Classification System (LCCS) – Classification Concepts and User Manual for Software Version 2. [Online]. Disponível em http://www.fao.org/docrep/008/y7220e/y7220e00.htm. Data de acesso: 03.11.2012.

Dufourmont, H., 2012. GIMES Initial Operations Land Service. Geoland2 forum, 18 – 19 October 2012, Copenhagen.

Duhamel, C., 1998. First approximation of a reference land use classification, Report to the FAO

EC, 2004. Building a European information capacity for environment and security. A contribution to the initial period of the GMES Action Plan (2002-2003).

EC, 2004. Building a European information capacity for environment and security. A contribution to the initial period of the GMES Action Plan (2002-2003).

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., and Snyder, P.K., 2005. Global consequences of land use. Science, 309: 570–574.

Foody, G., T. Warner, e M. Nellis, 2009. A look to the future. The SAGE Handbook of Remote Sensing, Ed. T. Warner, M. Nellis, e G. Foody. Thousand Oaks: SAGE Publications Inc.

Foody, G. M., 2004, Sub-pixel methods in remote sensing, in in S.M. de Jong and F.D. van der Meer (eds), Remote sensing image analysis – including the spatial domain, Dordrecht: Kluwer Academic Publishers.

Foody, G. M., 2002, Status of land cover classification accuracy assessment, Remote Sensing of the Environment, 80: 185-2001.

Foody, G.M., 1999, Image classification with a neural network: from completely crisp to fully-fuzzy situations, in P.M. Atkinson and N.J. Tate (eds), Advances in Remote Sensing and GIS analysis, Chichester: Wiley&Son.

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. and Schaaf, C., 2002. Global land cover mapping from MODIS: algorithms and early results. Remote Sensing of Environment, 83: 287–302.

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and Wickham, J., 2011. Completion of the 2006 National Land Cover Database for the Conterminous United States, PE&RS, Vol. 77(9):858-864.

Fry, J., Coan, M., Homer, C., Meyer, D., and Wickham, J., 2009. Completion of the National Land Cover Database (NLCD) 1992– 2001 land cover change retrofit product: U.S. Geological Survey Open-File Report 2008–1379, 18 p.

Georgi, B, and C. Hoffermann, 2012. Spatial planning for European needs, Geoland2 forum, 18 – 19 October 2012, Copenhagen.

Giri, C., 2012. Brief overview of remote sensing of land cover. Remote Sensing of Land Use and Land Cover, Ed. C. Piri, Boca Raton: Taylor & Francis.

GMES Global Land Working Group, 2008. Global component of the GMES Monitoring Core Service.

GSE Land Team, 2006, GSE Land Service Prospectus; ITD-0421-RP-0013-S3.

Homer et al., 2007. Completion of the 2001 National Land Cover Database for the Counterminous United States. Photogrammetric Engineering and Remote Sensing, 73(4) 337-341

Homer, C. C. Huang, L. Yang, B. Wylie, and M. Coan. 2004. Development of a 2001 National Landcover Database for the United States. Photogrammetric Engineering and Remote Sensing, 70 (7): 829-840

INSPIRE Drafting Team Data Specifications, 2007, Definition of Annex Themes and Scope.

IG-LMCS (Implementation Group on GMES Land Monitoring), 2007. GMES Fast Track Land Monitoring Core Service Strategic Implementation Plan.

Jensen, J., J. Im, P. Hardin, e R. Jensen, 2009. Image classification. The SAGE Handbook of Remote Sensing, Ed. T. Warner, M. Nellis, e G. Foody. Thousand Oaks: SAGE Publications Inc.

Jensen, J.R., 1996, Introductory digital image processing: a remote sensing perspective, Upper Saddle River, NJ: Prentice Hall, 2nd Ed.

Jochum, M., and R. Lacaze. 2012. Towards an operation GMES land monitoring service. Geoland2 forum, 18 – 19 October 2012, Copenhagen.

Lambin, E., B. Turner, H. Geist, S. Agbola, A. Angelsen, et al. 2001. The causes of land-use and land-cover change: moving beyond the myths. Glob. Environ. Change 11(4):261–69

Loveland, T. R., Reed, B. C., Brown, J. F., Ohlen, D. O., Zhu, Z., Yang, L., and Merchant, J. W., 2000. Development of a global land cover characteristics database and IGBP DISCover from 1 km AVHRR data. International Journal of Remote Sensing, 21(6–7): 1303– 1365.

Lu, D, E. Moran, S. Hetrick, and G. Li, 2011. Land-use and land-cover change detection, Q. Weng (Ed.), Advances in Environmental Remote Sensing Sensors, Algorithms, and Applications, CRC Press Taylor & Francis Group, New York.

Lu, D., e Q. Weng, 2007. A survey of image classification methods and techniques for improving classification performance. International Journal of Remote Sensing, 28 (5): 823–870

Lu, D. and Weng, Q., 2004, Spectral Mixture Analysis of the Urban Landscape in Indianapolis with Landsat ETM+ Imagery, Photogrammetric Engineedring and Remote Sensing, 70 (9), pp. 1053-106

Rocchini, D., e C. Ricotta, 2007. Are landscapes as crisp as we may think? Ecological Modelling, 204: 535–539.

Stehman, S.V., 1999, Basic probability sampling designs for thematic map accuracy assessment, International Journal of Remote Sensing, 20: 2423–2441.

Stehman, S., e G. Foody, 2009. Accuracy assessment. The SAGE Handbook of Remote Sensing, Ed. T. Warner, M. Nellis, e G. Foody. Thousand Oaks: SAGE Publications Inc.

Stehman, S.V., 1999, Basic probability sampling designs for thematic map accuracy assessment, International Journal of Remote Sensing, 20: 2423–2441.

United Nations, International Standard Industrial Classification (ISIC), Rev. 3

http://unstats.un.org/unsd/cr/registry/regcst.asp?Cl=2

Vogelmann, J.E., Howard S.M., Yang L., Larson C.R., Wylie B.K., and Van Driel N., 2001. Completion of the 1990s National Land Cover Data Set for the Conterminous United States from Landsat Thematic Mapper Data and Ancillary Data Sources. Photogrammetric Engineering and Remote Sensing, 67:650-662

Xian, G., C. Homer, J. Fry, 2009. Updating the 2001 National Land Cover Database land cover classification to 2006 by using Landsat imagery change detection methods. Remote Sensing of Environment, 113(6):1133-1147.

Wilkinson, G.G., 2005, Results and implications of a study of fifteen years of satellite image classification experiments, IEEE Transaction on Geosciences and Remote Sensing, 43:3, 433-440

Wulder, M., J. White, S. Goward, J. Masek, J. Irons, M. Herold, W. Cohe, T. Loveland, and C. Woodcock, 2008. Landsat continuity: Issues and opportunities for land cover monitoring. Remote Sensing of Environment, 112: 955–969.