General Surveillance of Genetically Modified Crops

Possibilities of GIS and Remote Sensing

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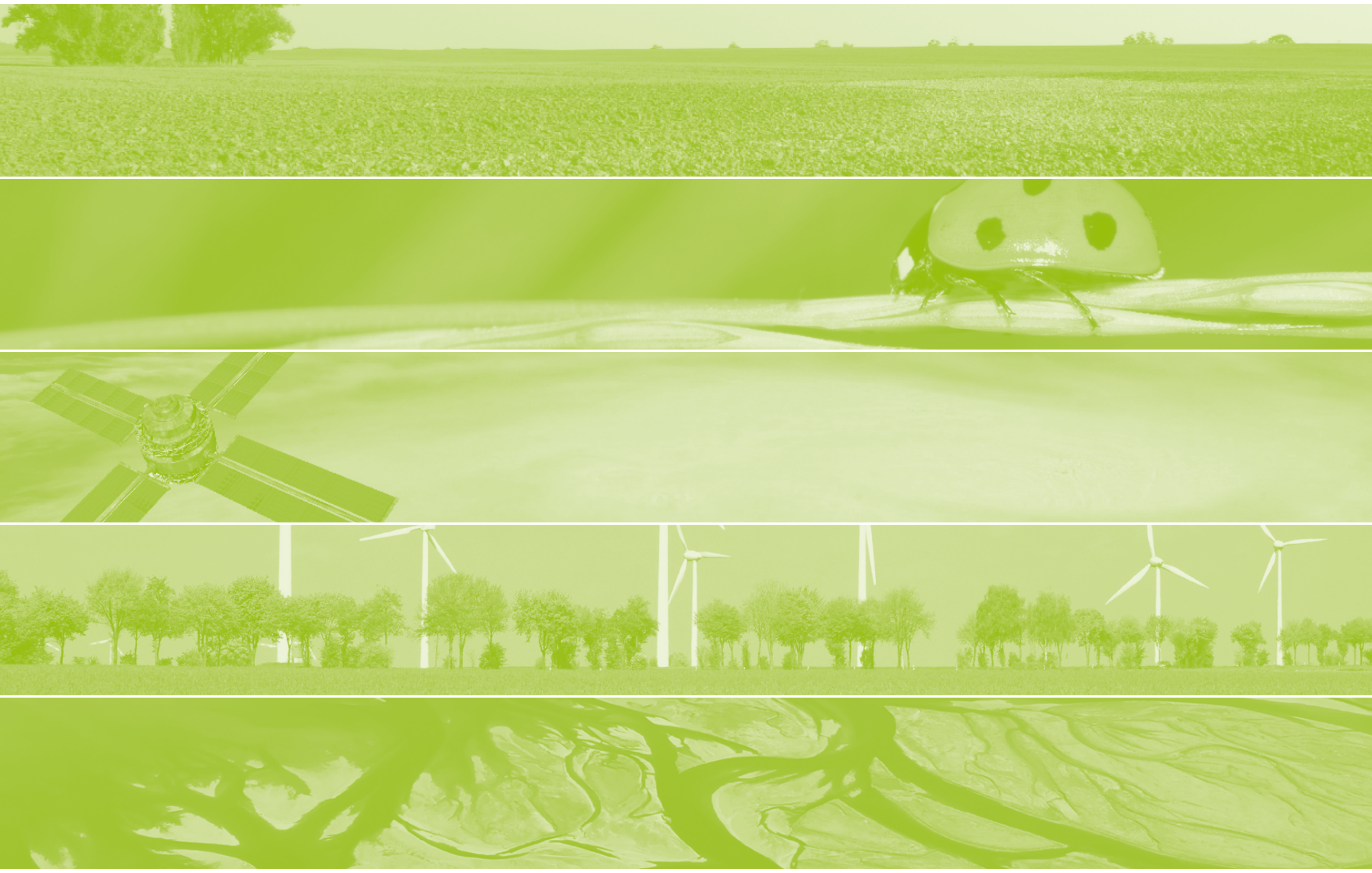

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General Surveillance of Genetically Modified Crops

Commissioned by the Ministry of Housing, Spatial Planning and the Environment (VROM), The Hague

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G.J. Roerink and M.H.G.I. Danes

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Abstract

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According EU legislation a General Surveillance is necessary “to monitor for unanticipated adverse effects of genetically modified organisms (GMOs) on the environment”. In this report a prototype of a monitoring system for such a General Surveillance is introduced on the basis of time series analysis of NDVI satellite images, as a proof of principle. The plant phenology is described in a quantitative way and different years are analysed and compared. The detected extreme differences are analysed in detail to determine whether it could be associated with GMOs. Weather conditions and human behaviour are distinguished to be the main driving forces for the detected anomalies. So far, this method is only suitable for the detection of unexpected effects on vegetation in natural areas. For real application for GS purposes, it may be possible to further develop and enhance the proposed prototype method.

Keywords: genetically modified crop, general surveillance, remote sensing, GIS, NDVI, time series, HANTS, ecological monitoring, plant phenology

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Preface

This report highlights the main results of the research project 'Possibilities of GIS and Remote Sensing for General Surveillance of Genetically Modified Crops'. It is funded by the Ministry of Housing, Spatial Planning and the Environment (VROM) and conducted in close cooperation with the project steering group, consisting out of the following members:

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The authors would like to thank the members of the project steering group for all their useful comments, questions and contributions.

Summary

According EU legislation a General Surveillance (GS) is necessary *'to monitor for unanticipated adverse effects of genetically modified organisms (GMOs) on human health and the environment'* (Lecoq et al., 2007) for importing and cultivating GMOs. Since unanticipated adverse effects can mean anything anywhere, many EU member states are struggling with their design of a GS. It is unclear what the unanticipated adverse effects may be or where/when they occur; therefore GS faces three major steps (EFSA, 2004; Wilkinson et al., 2003):

- GS should be able to observe unusual effects;
- GS has to determine whether unusual effects are adverse;
- GS should be able to determine whether the adverse effects can be associated with the GMOs and not with other aspects that origin from a dynamic agro-environment.

Once an observation is considered to be unusual, adverse and associated with the cultivation GMOs, a more in-depth study should be carried out to confirm its relation with GM crops (Bartsch et al., 2006). This research only focuses on the first step, i.e. the development of a method to observe unusual effects. Remote sensing is identified as one of the possible information sources for such a GS, as satellite images provide objective and uniform information of the land surface with complete coverage. Vegetation development may be a good indicator for environmental health, including soil health. By using remote sensing, the detection of unexpected effects of GMOs is limited to monitoring vegetation dynamics.

The objective of this research is formulated as *'To develop a method, based on GIS and Remote Sensing techniques, that is able to monitor unusual effects on vegetation that could be associated with GM crops in The Netherlands'.*

This research is subdivided into two phases. The objective of phase I was to explore the possibilities of GIS and Remote Sensing techniques for GS, where as the objective of phase II was to see how the different techniques could be translated to practice.

In order to observe unusual effects, one approach is to quantify the annual vegetation dynamics and compare this with a reference scenario. Vegetation indicators can be derived from:

- Historical satellite images;
- Knowledge and experiences of the 'observer' (e.g. farmers, inspectors, flora and fauna surveyors) (EFSA, 2004);
- (Ecological) monitoring networks.

Phase I revealed that Remote Sensing is suitable to monitor possible developments in the vegetation dynamics. It operates by measuring the reflected or emitted radiation from the earth surface, from which several indicators of vegetation monitoring can be derived. The NDVI vegetation index is selected as best performing indicator, as it is relatively easy to measure, highly sensitive for vegetation changes and robust. There is a large variety in suitable satellite systems which produce remote sensing images; each one with its own specific spatial, temporal and spectral resolution. The MODIS satellite system is selected for this research in our case, since it has the highest resolution (250 m) of the remote sensing images that have a daily revisit time and are also available free of charge.

In Phase II of this research a method is developed to monitor unusual effects on vegetation in the Netherlands for natural areas only, because the agricultural areas, by definition, have changing vegetation patterns over the

years due to their changing cropping system. First of all the vegetation dynamics are objectively quantified by a time series analysis of satellite images. Hereafter, the agricultural areas are masked and ultimately the most extreme changes over the years are identified as hot-spots. These hot-spots are analysed in detail with aerial photographs, land cover information and expert knowledge to come to a plausible explanation for the extreme changes in vegetation dynamics. In the cases where the cause of change could not be discovered, the hot-spot is defined as an observation of an unusual effect on vegetation.

The developed method is applied to three years of satellite images, to be known 2003 (relatively dry with a cold winter) and 2007 and 2008 (both relatively wet). The time series of satellite images consisted out of 16-days-maximum-NDVI composites of the MODIS satellite, where the NDVI is a vegetation indicator based on the different absorption features of red and near-infra-red radiation of vegetation versus other surface elements (soil, rock, water, etc). The HANTS algorithm (see also Chapter **7**) is used to perform a time series analysis on the NDVI images. The temporal NDVI profile is characterised by the average NDVI and the cosine functions of one year and six months. In an iterative process the erroneous outliers (cloud affected and missing data) are rejected. In this way an objective and quantitative characterisation of the vegetation dynamics is performed, which makes it possible to analyse the results of the different years among each other and in relation to major drivers, such as weather conditions and human interventions.

The general trends of the calculated temporal NDVI profiles between the years have a strong correlation with meteorological parameters as precipitation and temperature. However, the method detects extreme outliers within the general trend as well. Therefore, it can be concluded that the method is able to monitor unusual effects on vegetation, limited to natural areas. Not only differences in the average amount of vegetation between the years forms the basis of the analysis, also differences in seasonal changes (annual amplitude) and differences in the start/peak/end of the growing season (annual phase) are detected and quantified.

Five hot-spots are analysed in detail and it was attempted to find a plausible explanation for the unusual effect on vegetation by (i) recognising the land cover class from the LGN land cover map of the Netherlands and (ii) looking at higher resolution to the hot-spots with aerial photographs from 2003 and 2006. It could be identified that for three areas human interventions were the cause for the unusual effect, while another one could be explained by a natural process. However the last one, a shift of the growing season in time, could not be explained so far, and could be defined as an observation of a truly unusual effect on vegetation.

The used MODIS input images and therefore also the resulting HANTS outcomes have a resolution limited to 250 m. This is not sufficient to detect changes at field level, especially given the relative small parcel sizes and heterogeneous land cover in the Netherlands. However, this resolution is high enough to detect changes within natural areas, like the Veluwe national park, Biesbosch wetlands or Oostvaardersplassen national park. The moderate resolution allows making a relatively quick analysis, covering the extent of the Netherlands or even Europe and therefore shows potential as a prototype method for further enhancement aimed at operational General Surveillance.

The currently described method is only able to monitor natural areas, as arable farming induces each year major changes in vegetation phenology and therefore is always classified as ‘extreme’ changes in vegetation. The GS in principle requests that also agricultural areas are monitored, so a similar method could be developed for that purpose as well. A way to deal with agricultural areas might be to look at averaged temporal NDVI profiles of specific agricultural crops within larger regional units (municipalities, provinces, etc.) instead of evaluating individual pixels. By doing so the averaged temporal NDVI profiles, describing the crop phenology for each year and specific regional unit, can be quantitatively compared and analysed again.

Samenvatting

EU-wetgeving geeft aan dat een General Surveillance (GS) nodig is '*om onvoorziene negatieve effecten van genetisch gemodificeerde organismen (GGOs) op de volksgezondheid en het milieu te monitoren'* (Lecoq et al., 2007) bij de introductie en cultivatie van GGOs. Veel EU-lidstaten worstelen met het ontwerpen en inrichten van hun GS, aangezien de term 'onvoorziene negatieve effecten' niet verder gespecificeerd wordt. Omdat het niet duidelijk is wat onvoorziene negatieve effecten zouden kunnen zijn en waar ze zouden kunnen optreden moet een GS aan drie voorwaarden voldoen:

- GS moet onvoorziene effecten kunnen waarnemen;
- GS moet kunnen vaststellen of de onvoorziene effecten negatief zijn;
- GS moet kunnen vaststellen of onvoorziene negatieve effecten kunnen worden geassocieerd met GGOs en niet het gevolg zijn van andere aspecten van het natuurlijke agro-ecosysteem.

Als een observatie aan de drie hierboven genoemde criteria voldoet moet een diepgaand vervolgonderzoek vaststellen of dit onvoorziene negatieve effect daadwerkelijk het gevolg is van de introductie en/of cultivatie van GGOs in de leefomgeving (Bartsch et al., 2006).
Het in dit rapport beschreven onderzoek concentreerde zich alleen op de eerste stap, namelijk het ontwikkelen van een methode om onvoorziene effecten te kunnen detecteren. Remote sensing is geïdentificeerd als een van de mogelijke informatiebronnen voor een dergelijke GS, aangezien satellietbeelden objectieve, uniforme en landsdekkende informatie kunnen leveren. Een mogelijkerwijs goede indicator voor de gesteldheid van de leefomgeving is vegetatiedynamiek. Deze laatste kan door remote sensing technieken worden vastgesteld. Deze opzet beperkt het detecteren van onvoorziene effecten tot monitoren van de vegetatiedynamiek.

De doelstelling van dit onderzoek is gedefinieerd als '*Het ontwikkelen van een methode die, met behulp van GIS en remote sensing-technieken, onvoorziene effecten op vegetatie kan monitoren die gerelateerd zouden kunnen worden aan genetische gemodificeerde gewassen in Nederland'.*

Het onderzoek is opgedeeld in twee fases. Doelstelling van fase I was het onderzoeken van de mogelijkheden van GIS en remote sensing-technieken voor het opzetten van een GS. Fase II gaat meer in op de vraag hoe deze technieken kunnen worden vertaald naar de praktijk, oftewel het ontwerpen van de monitoring-methode zelf.

Een benadering om onvoorziene effecten te kunnen detecteren is om het jaarlijkse verloop van de vegetatiedynamiek te kwantificeren en dit te vergelijken met een referentie scenario. Vegetatie indicatoren kunnen verkregen worden door middel van:

- (historische) satellietbeelden;
- kennis en ervaring van praktijkmensen (boeren, inspecteurs, flora en fauna veldwerkers, etc.);
- (ecologische) monitoring netwerken.

Fase I maakte duidelijk dat remote sensing is geschikt om mogelijke ontwikkelingen van de vegetatie dynamiek te monitoren. Door middel van het registreren van gereflecteerde of geëmitteerde straling afkomstig van het aardoppervlak kunnen verschillende vegetatie indicatoren worden afgeleid. De NDVI-vegetatie index is geselecteerd als meest geschikte indicator, aangezien deze relatief eenvoudig te berekenen is, gevoelig voor veranderingen en robuust in gebruik. Een scala aan geschikte satelliet sensoren met bijbehorende beelden is beschikbaar, elk met zijn specifieke ruimtelijke, temporele en spectrale resolutie. De MODIS-satellietsensor is

geselecteerd voor dit specifieke onderzoek, omdat het de hoogste resolutie (250 m) heeft van de vrij beschikbare remote sensing beelden met een dagelijkse beschikbaarheid.

Gedurende fase II van het onderzoek is een methode ontwikkeld en getest voor het monitoren van onvoorziene effecten op de vegetatiedynamiek in natuurgebieden. Landbouwgebieden zijn gemaskeerd in het onderzoek, omdat deze per definitie al een veranderend jaarlijks landgebruik hebben door de gewaskalender. De methode behelst een aantal stappen waarvan de eerste de kwantificering van de plant-fenologie was door middel van een tijdsreeksenanalyse op de satellietbeelden. Hierna werden de landbouwgebieden gemaskeerd en ten slotte werden de meest extreme verschillen tussen de jaren geïdentificeerd als hot-spots. De hot-spots zijn verder in detail geanalyseerd met behulp van luchtfoto's, landgebruikkaarten en ervaringsexpertise om tot een plausibele verklaring voor de gevonden verschillen te komen. In het geval dat de verklaring niet kon worden gevonden werd de hot-spot verklaard tot een daadwerkelijk onvoorzien effect op vegetatie.

De ontwikkelde methode is toegepast op tijdsreeksen van satellietbeelden van drie jaren, te weten 2003 (relatief droog met een koude winter) en 2007 en 2008 (beide relatief nat). De gebruikte satellietbeelden zijn 16-daagse-maximum-NDVI composieten van de MODIS satellietsensor, waarbij de NDVI een vegetatie indicator is gebaseerd op de verschillende absorptie-karakteristieken van rood en nabij infra-rood licht van vegetatie versus andere oppervlakken (rots, zand, water, etc.). Het HANTS algoritme (zie hoofdstuk 7) is gebruikt om de NDVI-tijdsreeksenanalyse uit te voeren. Het temporele NDVI-profiel wordt gekenmerkt door een gemiddelde NDVI en de jaarlijkse en halfjaarlijkse cosinus functies. Gedurende een iteratief proces worden negatieve uitbijters (bewolkte en missende rastercellen) verwijderd. Hierdoor is een objectieve en kwantitatieve karakterisatie van de vegetatie-dynamiek mogelijk en kunnen de resultaten van de verschillende jaren onderling worden vergeleken en geanalyseerd in relatie tot de grootste impactbronnen, zoals weersomstandigheden en menselijke interventies.

De algemene trend van de berekende temporele NDVI-profielen tussen de verschillende jaren is sterk gecorreleerd aan meteorologische parameters, zoals neerslag en temperatuur. Echter, extreme uitbijters binnen of buiten de algemene trend worden door de methode ook waargenomen. Hierdoor kan worden geconcludeerd met deze methode het mogelijk wordt om onvoorziene effecten of de vegetatiedynamiek te monitoren binnen natuurgebieden. Niet alleen verschillen in de gemiddelde hoeveelheid vegetatie tussen de jaren vormen de basis voor de analyse, ook seizoensverschillen tussen zomer en winter en veranderingen in de start/piek/eind van het groeiseizoen worden waargenomen en gekwantificeerd.

Vijf hot-spots zijn geanalyseerd in detail en er is getracht een mogelijke verklaring te geven voor het gevonden onvoorziene effect met behulp van (i) bepaling van het landgebruik van de LGN-landgebruikkaart van Nederland en (ii) het gebruik van hoge resolutie luchtfoto's van 2003 en 2006. Voor drie hot-spots was het mogelijk om het onvoorziene effect te verklaren als gevolg van menselijk ingrijpen; een vierde kon worden geïdentificeerd als een natuurlijk proces. Echter, voor de laatste hot-spot, een verschuiving van het groeiseizoen in de tijd, is nog geen afdoende verklaring gevonden en kan zodoende worden gedefinieerd als een waarlijk onvoorzien effect op de vegetatie dynamiek.

De gebruikte MODIS-beelden en zodoende ook de HANTS-resultaten hebben een resolutie van 250 m. Dit is niet hoog genoeg om veranderingen op veldniveau te karteren, helemaal gezien de relatief kleine percelen en het heterogene landgebruik in Nederland. De resolutie is echter wel hoog genoeg om veranderingen waar te nemen binnen natuurgebieden, zoals de Veluwe, de Biesbosch of de Oostvaardersplassen. De 250 m-resolutie maakt het mogelijk om een relatief snelle scan van Nederland of Europa uit te voeren en heeft als zodanig de potentie in zich om als prototype methode verder te kunnen worden doorontwikkeld tot een operationele General Surveillance.

Met de in dit rapport beschreven methode is het alleen mogelijk om natuurgebieden te monitoren, omdat in deze gebieden in principe geen grote veranderingen tussen opeenvolgende jaren wordt verwacht. Landbouwgebieden met hun jaarlijkse gewasrotaties zullen er bij deze methode altijd uitspringen als extreme veranderingen. De General Surveillance verlangt echter ook dat landbouwgebieden gemonitoord worden. Dit kan met de ontwikkelde methode ook gedaan worden, als niet meer gekeken wordt op het kleinste schaalniveau (individuele rastercel) maar op een schaalniveau hoger, oftewel gemiddelde temporele NDVI-profielen per gewas voor regionale eenheden zoals gemeentes of provincies. Hierdoor wordt het weer mogelijk om de NDVI-profielen, die de plant-fenologie per gewas, per jaar en per regio beschrijven, tussen de jaren kwantitatief te vergelijken en analyseren.

List of abbreviations

BRP	Basis Registratie Percelen
DOD	Degree of OverDeterminedness
EFSA	European Food Safety Authority
EVI	Enhanced Vegetation Index
FET	Fit Error Tolerance
GIS	Geographic Information System
GM	Genetically Modified
GMO	Genetically Modified Organism
GS	General Surveillance
HANTS	Harmonic ANalyses of Time Series
IDRT	Invalid Data Rejection Threshold
LAI	Leaf Area Index
LGN	Landelijk Grondgebruik Nederland
MIR	Middle Infra Red
MODIS	Moderate Resolution Imaging Spectroradiometer
NDVI	Normalized Difference Vegetation Index
NDFF	National (= Netherlands) Database Flora and Fauna
NOF	Number Of Frequencies
NIR	Near Infra Red
RS	Remote Sensing
SF	High/Low Suppression flag
TIR	Thermal Infra Red
VIS	Visible part of electromagnetic spectrum

1 Project introduction

1.1 Background

According EU legislation a General Surveillance (GS) is necessary *'to monitor for unanticipated adverse effects of genetically modified organisms (GMOs) on human health and the environment'* (Lecoq et al., 2007) for importing and cultivating GMOs. In other words, the whole country needs to be monitored for the possible unforeseen consequences of the local introduction of GMOs. Since unanticipated adverse effects can mean anything anywhere, many EU member states are struggling with their design of a GS.

Agreed upon is that applicants need to perform a surveillance at field and farm level. However, the surveillance of interactions between GMOs from different applicants at regional and national level is beyond the applicant's capability (EFSA, 2004). It may therefore be the responsibility of the government to develop a practical and cost effective mechanism that carries out a GS at national scale.

Even on a national scale, unanticipated adverse effects are most likely to occur on locations where the environmental exposure is high. So it is considered to be a good starting point in any general surveillance plan, to evaluate the development and the surrounding environment of genetic modified (GM) crop cultivations (Bartsch et al., 2006). As in the Netherlands no GM crop cultivation takes place up to now (2010), no special attention could be given to this last point.

1.2 Demarcations

This report explores the possibilities to implement GIS and Remote Sensing techniques in a GS, which leads to the following demarcations:

- The focus will be on evaluating potential effects of GM crop cultivation. With Remote Sensing it is possible to monitor unusual effects on vegetation in The Netherlands. This includes unusual effects on the vegetation as a result of GM-induced effects the soil ecosystem functioning.
- GIS will be used to evaluate whether observed effects can be associated to any independent processes, like changes in climate or land-use.

1.3 Objective

Taken into account the demarcations described above, we can define the project objective as follows:

'To develop a method, based on GIS and Remote Sensing techniques, that is able to monitor unusual effects on vegetation that could be associated with GM crops in The Netherlands.'

1.4 Report outline

This research is subdivided into two phases. The objective of phase I is to explore the possibilities of GIS and Remote Sensing techniques for GS, where as the objective of phase II is to see how the different techniques can be translated to practice.

The following chapter starts with a brief introduction about the GS. In the next chapter different Remote Sensing techniques are explained. Chapter 4 treats the implementation of GIS and the available source information where after in chapter 5 the work of phase I is summarized and recommendations are drafted for phase II. Chapter 6 gives the outline for the research in phase II. Chapter 7 explains the used method (HANTS algorithm) for time series analysis of remote sensing images. The results of this time series analysis are described in chapter 8; together with a detailed study of outliers, or the ability to observe 'unusual effects on vegetation', the key question in this research. The benefits, drawbacks and prospects of the developed monitoring method are discussed in chapter 9 and conclusions are drawn in the last chapter.

2 General Surveillance

2.1 Introduction

Like the introduction stated, the objective of a GS is to monitor for unanticipated adverse effects of GMO cultivation. One additional important concept is that a GS should be a hypothesis free method. However, since it is unclear what the unanticipated adverse effects may be or where/when they occur; GS faces three major steps (EFSA, 2004; Wilkinson et al., 2003):

- GS should be able to observe unusual effects;
- GS has to determine whether unusual effects are adverse;
- GS should be able to determine whether the adverse effects can be associated with the GMOs and not with other aspects that origin from a dynamic agro-environment.

Once an observation is considered to be unusual, adverse and associated with the cultivation GMOs, a more in-depth study should be carried out to confirm its relation with GM crops (Bartsch et al., 2006).

This research only focuses on the first step, i.e. the development of a method to observe unusual effects in vegetation dynamics. In order to observe unusual effects, one approach is to quantify the annual vegetation dynamics and compare this with a reference scenario. Vegetation indicators can be derived from:

- Historical satellite images;
- Knowledge and experiences of the 'observer' (e.g. farmers, inspectors, flora and fauna surveyors) (EFSA, 2004);
- (Ecological) monitoring networks.

Especially since possible unusual effects are most likely to occur where the level of environmental exposure is highest, farmers involved in GM cultivation are considered to be a valuable source of information. *"Acknowledging this, the Plant Biotechnology Industry has developed a harmonized general surveillance approach based on farmer questionnaires"* (Lecoq et al., 2007).
Additional to satellite images and farmers questionnaire, existing monitoring networks are considered to be very useful as validation. Examples of networks are: *"(a) Meteorological services; (b) Extension services of relevant national authorities; and (c) Networks that consider the GM crops as one of many factors in the agronomic landscape, taking into account factors such as changes in general agricultural practices, climate, sources of pollution etc."* (Lecoq et al., 2007).
However, this research only explored the possibilities of using Remote Sensing images; future research could be elaborated to include information from other sources like farmers' questionnaires and ecological monitoring networks.

2.2 Current status in the Netherlands

At the moment this report was lined up (2010), no GM crops were being commercially cultivated within the Netherlands. In spite of lacking GM cultivations, this report explored the possibilities to implement GIS and Remote Sensing techniques in a GS. Furthermore the lacking GM cultivations provides an exquisite opportunity to establish national baselines.

3 Remote Sensing

Remote sensing (RS), also called earth observation, refers to obtaining information about objects or areas at the Earth's surface by using electromagnetic radiation (light) without being in direct contact with the object or area. Without realizing it, remote sensing is day to day business for people. Reading the newspaper or watching cars driving in front of you are all remote sensing activities. The human eye registers the solar light, reflected by any object, and the brain interprets colours, grey tones and intensity variations. However, the human eye is limited to register only a small part of the total electromagnetic spectrum i.e. approximately 400 to 700 nm. In remote sensing various kinds of tools and devices are used to make electromagnetic radiation outside this visible (VIS) range from 400 to 700 nm, especially the near-infrared (NIR), middle-infrared (MIR), thermal-infrared (TIR) and microwaves (see Figure 1) (Lillesand and Kiefer, 1994). Increasingly, remote sensing is used to acquire information about environmental processes such as agricultural crop growth, land cover changes, deforestation, vegetation dynamics, water quality dynamics, urban growth, etc.

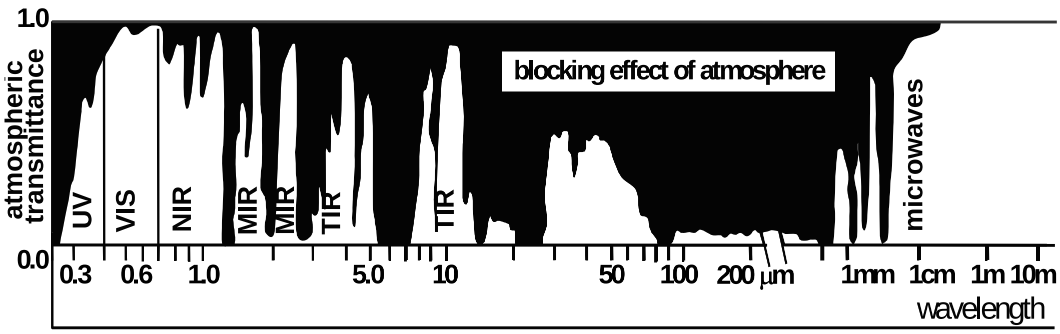

Figure 1
Atmospheric transmittance for radiation as a function of the wavelength

3.1 Spectral signatures of water, soil and vegetation

When radiation hits an object, it can be transmitted, absorbed or reflected. The mutual amplitude of these processes is determined by the properties of the object. With remote sensing the amount of reflected solar radiation can be measured as a function of wavelength, called spectral reflectance. Figure 2 illustrates the spectral reflectance of some typical objects.
Water absorbs most of the incoming radiation and only reflects a small amount (particularly in the visible part of the spectrum; at longer wavelengths water does not reflect any significant radiation).
Soils exhibit quite a smooth spectral reflectance curve. Distinct features are found in narrow spectral bands due to absorption by minerals and iron oxide. Broader features occur near 1.4 µm and around 1.9 µm, due to absorption by the moisture content. The absorption by moist also causes the gradually decreasing reflectance with increasing wavelength in the MIR region. The soil moisture causes the spectral reflectance of a wet soil to be lower than that of a dry soil.
Vegetation, on the other hand, shows a very characteristic reflectance curve. The reflectance in the visible part of the spectrum is low due to absorption of this radiation by chlorophyll in the green parts of a plant. In the NIR region hardly any absorption occurs, and reflectance is determined by the amount of transitions between cell walls and air vacuoles in the leaf tissue. As a result, NIR reflectance of green vegetation is high, and a steep

slope occurs in the reflectance curve at about 0.7 μm (the so-called red-edge region). In the MIR region we observe a similar influence of moist, as observed for soils.

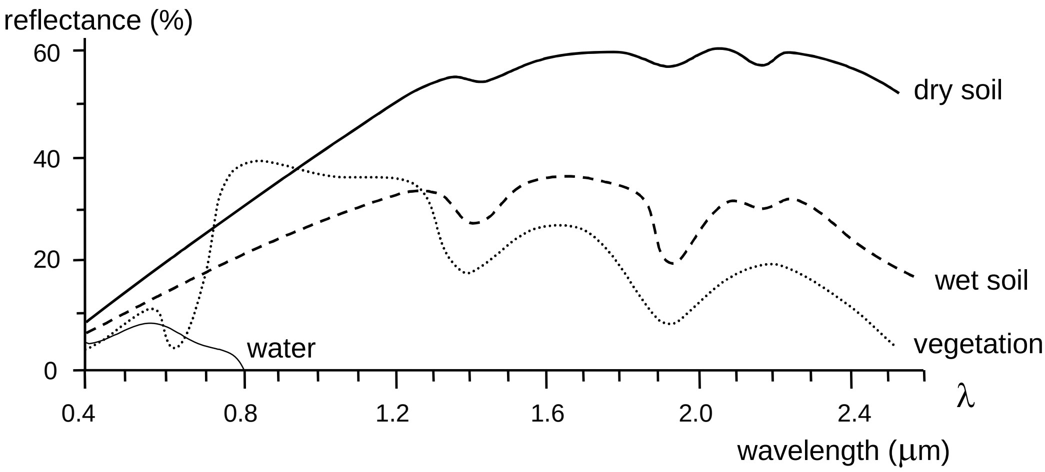

Figure 2
Typical spectral reflectance curves for water, soil and vegetation

In the TIR part of the spectrum the amount of emitted radiation is measured. This amount can be related to the temperature of the feature observed. This provides information on, e.g., the (evapo-)transpiration of the surface and thus gives relevant information for energy balance studies.

3.2 Temporal changes

Also in time the spectral signatures can change as the result from crop rotations, weather conditions, urbanisation, plant sickness or other reasons (like for example any effects due to GM crops!). For example, Figure 3 shows the effect of grain blight infection on wheat. It is clear that the photosynthesis process in the infected wheat is not functioning properly anymore, as the absorbed fraction of visible light is less.

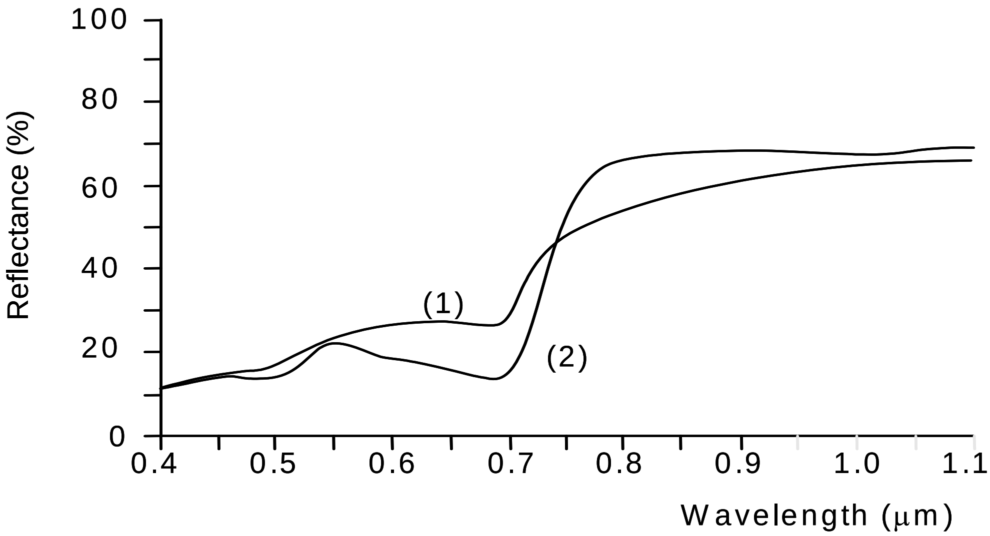

Figure 3
Spectral signatures of (1) grain blight infected wheat leaves and (2) healthy wheat leaves (Keegan et al., 1956)

3.3 Resolution

The resolution of a satellite sensor is an important aspect of the applicability of remote sensing images. Three distinct resolutions can be defined:

- The spatial resolution is the size of raster cells of the image. Dependent of the size it is possible to observe only the coarse land objects (large lakes, natural vs agricultural areas, etc.) or also make observations at field level (farm parcels, roads, etc.). Typical resolutions for the first and latter case are respectively 1 km and 30 m.
- The temporal resolution is the time in-between two acquired successive images of the same location by a certain satellite sensor. Unfortunately, in practice the temporal resolution has a negative correlation with the spatial resolution, which means that high temporal resolutions (daily images) correspond to low spatial resolutions (>250 m). Not all satellite sensors are capable of providing daily coverage.
- The spectral resolution depends on the number of spectral bands and the spectral coverage of the bands. To map vegetation at least a red and NIR spectral band should be available. Higher spectral resolution data, i.e. the number of distinct colours of light that can be distinguished in the data, carries more information that can be utilized for analysis.

3.4 Satellite systems

Several vegetation indicators can be derived from satellite images. To monitor temporal behaviour of vegetation throughout a year, at least monthly cloud free observations are necessary. Clouds effectively block the land surface for observation by the satellite. The number of available images is related to revisit time and cloud cover. Given the fact that 50% of the earth is cloud covered at any time, we also have a large fraction of cloud covered days in the Netherlands. Monthly cloud free observations can only be achieved with a daily satellite revisit time. Table 1 gives an overview of common satellite imagery that can be used to monitor vegetation dynamics, i.e. which includes a red and NIR spectral band. It should also be mentioned that satellites have a typical operational lifetime of three to five years. For a true (GS) monitoring system continuity of observations from a sequence of earth observing satellites providing the relevant data is needed.

Table 1
Overview of commonly used satellite imagery that can be used for vegetation monitoring

Satellite	Resolution	Revisit time	Cost
Landsat	30 m	16 days	€ 0.02 per km^2
SPOT	10-20 m	8 days (daily off-nadir)	€ 0.53 per km^2
MODIS	250 m	daily	free downloadable
NOAA/AVHRR	1000 m	daily	free downloadable
RapidEye	5 m	5.5 days (daily off-nadir)	€ 0.95 per km^2
DMC	32 m	up to daily	€ 0.12 per km^2

3.5 Remote Sensing Indicators

As indicated in chapter 1 the purpose of this research is to develop a method to monitor with remote sensing any unanticipated effects of GM crops on other vegetation in The Netherlands. So to monitor these unanticipated effects, it is necessary to quantify the temporal and spatial behaviour of the vegetative development, or so-called *vegetation dynamics*. Remote sensing gives the possibility to measure and quantify several vegetation properties. This paragraph gives an overview of a number of possible vegetation indicators that can be measured by remote sensing techniques and that quantify the vegetation dynamics.

Surface Reflectance
The surface reflectance is the ratio of the reflected radiation over the incoming radiation. This can be calculated for each spectral band of a satellite sensor or as the total reflectance of the entire electromagnetic spectrum. The latter is called the albedo. Reflectance and albedo are relatively easy to measure. As explained in section 3.1 the reflection of radiation from the red and NIR spectral band is very sensitive to vegetation dynamics. The broadband albedo however, is a kind of weighted average of all spectral bands and is less sensitive to map vegetation characteristics (sometimes no distinction can be made between bare soil and vegetation as they can have the same albedo).

Surface Temperature
The surface temperature can serve as a vegetation indicator as well, since green vegetation is relatively cold due to the transpiration process of plants. However there are serious disadvantages of using temperature as vegetation indicator as the strength of the radiative signal in the TIR part is low and thus a larger footprint (= spatial resolution) is necessary, compared to the surface reflectance. Furthermore it is difficult to compare images from different days, as they not only vary as a result of the evapotranspiration process, but also due the daily temperature cycle (warmest at noon, cold at night) and its dependency of the irregular behaviour of the weather conditions (one day it is warm, the next day it is cold).

Vegetation Indices
Several vegetation indices have been developed over the years. The basic principle of all vegetation indices is a certain ratio between reflected red and NIR radiation. The Normalized Difference Vegetation Index (NDVI) is the indicator with the longest track record back to 1979 (Tucker, 1979). It is defined as:

$$NDVI = \frac{NIR - red}{NIR + red} \tag{1}$$

The NDVI index ranges between 0 and 1 and has no physical meaning like the other indicators described in this paragraph. However, it is easy to measure and is very sensitive to temporal and spatial changes of the vegetation cover. Another advantage is also that it is not sensitive to weather conditions as for example temperature or humidity. Calculating the NDVI of water will result in negative values, bare soil has an NDVI that is approximately between 0.10 and 0.20 and green vegetation can score up to 0.80.

The Enhanced Vegetation Index (EVI) is an 'optimized' index designed to enhance the vegetation signal with improved sensitivity in high biomass regions and a correction for canopy background signal and certain atmospheric influences (Huete et al., 1997). The equation is defined as:

$$EVI = G \frac{NIR - red}{NIR + C_1\, red - C_2\, blue + L} \tag{2}$$

where NIR, red and blue are the surface reflectances in their specific spectral band, L is the canopy background adjustment factor and C_1, C_2 are the coefficients of the aerosol resistance term, which uses the blue band to correct for aerosol influences in the red band. G is the gain factor to stretch the results in the range from 0 to 1.

The two vegetation indices complement each other in global vegetation studies and improve upon the detection of vegetation changes and extraction of canopy biophysical parameters (Huete et al., 2002).

Table 2
NDVI and EVI values for typical land cover types

Object	Blue reflection (%)	Red reflection (%)	NIR reflection (%)	NDVI	EVI*
	8	21	30	0.18	0.12
Wet soil	7	14	19	0.15	0.08
Vegetation	4	5	40	0.78	0.63
Water	5	8	4	-0.33	-0.09

* where G = 2.5, C_1=6.0, C_2=7.5, L=1

LAI
The Leaf Area Index (LAI) is a ratio of the total upper leaf surface of vegetation divided by the surface area of the land on which the vegetation grows. LAI is a dimensionless value, typically ranging from 0 for bare ground to 8 for a dense forest.

The LAI can be measured by remote sensing as an empirical relationship of the NDVI (see Figure 4) or can be modelled in a more sophisticated way, using more input variables as well.

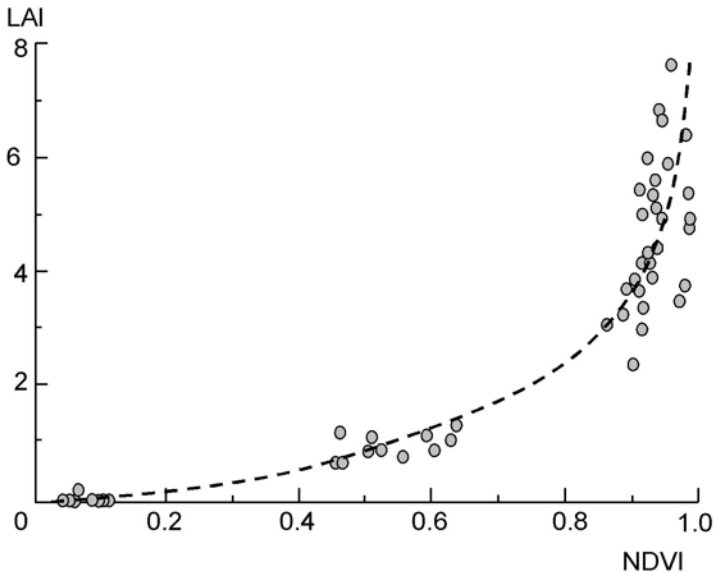

Figure 4
Relationship between NDVI en LAI (Buiten and Clevers, 1990)

Biomass production, Evapotranspiration, CO_2 flux
Biomass productions, as well as evapotranspiration and CO_2 flux are important vegetation indicators. However, they are less suitable for this research as they are measured only indirectly by remote sensing techniques. They are the outcomes of rather complex remote sensing models, where surface temperature and reflectance are used as input parameters, together with other variables.

Table 3 gives an overview of the dis-/advantages of the mentioned vegetation indicators.

Table 3
Overview of vegetation indicators and their characteristics

Vegetation indicator	Sensitivity to vegetation changes	Robustness to non-relevant processes	Physical meaning	Easiness to derive
Surface reflectance	+/-	+	+	+
Surface temperature	+	-	+	+
NDVI and EVI	++	+	-	+
LAI	+	+	+	+/-
Biomass, ET, CO2	+	+	+	-

3.6 Selected indicator and satellite system

Table 3 shows that the NDVI and EVI vegetation indicators score highs on our selection criteria for use in this study. The only exception is that they don't have a direct physical meaning, being indices, while the other indicators are direct physical quantities. However, for the purpose and exploratory nature of this work (vegetation monitoring) it is no problem, as we don't have to further process the data in for example crop growth models. Therefore the NDVI and EVI will be used as principal indicators during this research.

Figure 5
MODIS image of the Netherlands on 2 July 2008 (red/green/blue = MODIS band 1, 4, 3)

The NDVI and EVI will be derived from MODIS satellite images, as these images have the highest resolution of the freely available remote sensing images that have a daily revisit time (see Table 1). An example of a MODIS image is shown in Figure 5, where the MODIS bands 1 (red spectral band, 250 m resolution), band 4 (green spectral band, 500 m resolution) and band 3 (blue spectral band, resolution 500 m) are represented in respectively the colours red, green and blue. This visualization corresponds to how the human eye observes the earth as well; please note the white clouds in the upper right corner.

4 GIS analyses

4.1 Introduction to GIS

“A geographic information system (GIS) is a computer system for capturing, storing, querying, analyzing, and displaying geospatial data” (Chang, 2008). Geospatial data describes both locations and characteristics of spatial features, such as roads, land parcels, and vegetation stands on the Earth’s surface. Because of a diverse use of geospatial data, GIS is a commonly accepted technology in occupations like market research analyst, environmental engineers, and urban van regional planners.

During this research GIS will be used to determine and visualize the unusual effects, observed by Remote Sensing. Another major advantage of GIS is that it is relatively easy to carry out an overlay analysis. An overlay analysis can be used to see if there is a spatial relation between unusual observed effects and local changes, like changes in weather conditions or a change in land-use. One example of an overlay analysis can be found in Figure 6 and Figure 7.

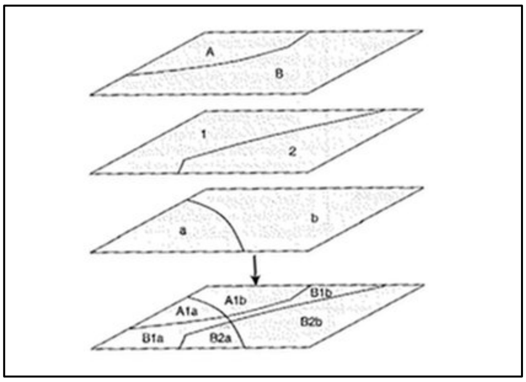

Figure 6
A raster data operation with multiple rasters (source: Chang, 2008)

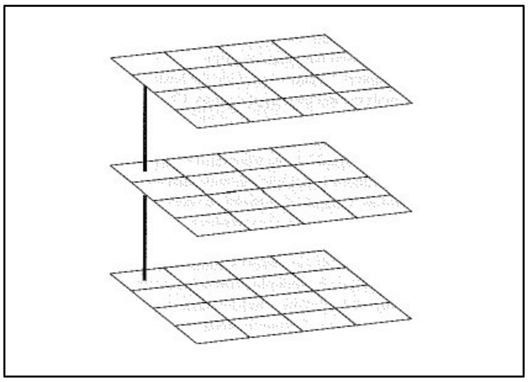

Figure 7
A vector-based overlay operation combines geospatial data from different layers (source: Chang, 2008)

4.2 Available GIS layers

To see if any of the observed effects can be explained, the observed effects can be overlayed with all kind of information layers, like:

- Land use;
- Crop rotation schemes;
- Meteorology.

Landelijk Grondgebruik Nederland (Land use database of the Netherlands, LGN)
A great deal of the spatial variability in the sampled values for flora and fauna can be explained by the type of land use. For the Netherlands every four years a new land use map is created, with a spatial resolution of 25 meters (Landelijk Grondgebruik Nederland, 2009). The purpose of this raster map is to visualize the land use, but it does not reveal information about the cultivated crops in arable farming for each year. To get more

information about the cropping calendar per parcel, additional information can be annually obtained from the BRP.

Basis Registratie Percelen (BRP)
For each agricultural parcel or environmental terrain the administrator has to register the annual crop rotation. Combined with the cadastral units, this result in the Basis Registratie Percelen (BRP) of The Netherlands.

Meteorology
Next to spatial dependency of observations, sampled values have a natural temporal dependency on climatic circumstances. Within The Netherlands, 35 metrological stations are situated, which daily measure climatic indicators like; temperature, amount and duration of precipitation, wind speed and direction, cloud cover, sunshine duration, humidity and potential evapotranspiration (KNMI, 2009).

4.3 Additional parameters

Besides satellite images, the GS could also consider other information types, like:
- Existing ecological monitoring networks;
- Farmers questionnaires.

Even though the latter mentioned information sources are neglected in the current research, this paragraph summarizes possible parameters that could be used in future GIS analyses.

Ecological monitoring networks
Additional information about flora and fauna can be derived from the national database for flora and fauna (NDFF). The Netherlands initialized the registration of nationally wide flora and fauna observations in 1998. Ever since the NDFF uses existing monitoring networks from private ecological data management organizations. Table 4 summarizes the organizations that participate in the NDFF. Additional the table contains information about the sample size and frequency.

Table 4
Private ecological data management organizations

Organization	Focus	Statistical unit	Research start	Observation frequency	Research magnitude
ANEMOON (Stichting Analyse Educatie en Marien Oecologisch Onderzoek)	Flora and fauna in the Dutch coastal waters	Not applicable	1993	Annual	approx. 130 sample locations
BLWG (Bryologische en Lichenologische werkgroep van KNNV)	Lichen	Lichen variety	1999	Five yearly	approx. 30 sample locations per year
EIS-NL (European Invertebrate Survey Nederland)	Wood louse, beatle, mollusc, parasite, vertebrate, arachnida, grasshopper, cricket, cockroach, earwig, fly, wasp, bee	Number of instects	Not available	Annual	Not available
FLORON (Stichting Floristisch Onderzoek)	Flora	Flora variety	1985	Annual	approx. 2.500 sample locations
NMV (Nederlandse Mycologische Vereniging)	Fungus	Fungus variety	1998	Annual	approx. 550 sample locations
RAVON (Reptielen-, Amfibieën- en Vissen Onderzoek Nederland)	Amphibian	Amphibian variety	1997	Annual	approx. 200 sample locations
RAVON (Reptielen-, Amfibieën- en Vissen Onderzoek Nederland)	Reptile	Reptile variety	1994	Annual	approx. 300 sample locations
SOVON (Vogelonderzoek Nederland)	Brood bird	Brood bird variety	1990	Annual	approx. 1.000 sample locations
SOVON (Vogelonderzoek Nederland)	Pasture bird	Pasture bird variety	1990	Annual	approx. 1.100 sample locations
SOVON (Vogelonderzoek Nederland)	Water bird	Water bird variety	1975	Annual	approx. 300 sample locations
Stichting Tinea	Small butterfly and microlepidoptera	Not available	Not available	Not available	Not available
Vlinderstichting	Butterfly	Butterfly variety	1990	Annual	approx. 600 sample locations
Vlinderstichting	Dragonfly	Dragonfly variety	1998	Annual	approx. 340 sample locations
VZZ (Vereniging voor Zoogdierkunde en Zoogdierbescherming)	Mammal	Daily active mamal variety	1994	Annual	approx. 300 sample locations
VZZ (Vereniging voor Zoogdierkunde en Zoogdierbescherming)	Bat	Bat variety	1986	Annual	approx. 800 sample locations

Questionnaires

Another important source of information can be derived from farmer questionnaires. Like stated in chapter 2 (General Surveillance), farmers have a large amount of local knowledge and experience since they are intensively involved in the cultivation of GM crops. It is obligatory for GM crop cultivators to monitor the effects of GM crops through a questionnaire.

5 Recommendations phase I

The purpose of this report is to find out whether GIS systems and Remote Sensing can be used to observe unusual effects in the vegetation dynamics. In this regard the difference between GIS systems and Remote Sensing should be clearly understood. Remote Sensing is a technique used to collect data about the earth surface by satellite systems, whereas GIS systems are used to determine whether the observed effect is unusual or not. During this research only satellite images will be used as input data, but this could be extended with information from farmers' questionnaires or existing ecological monitoring networks. The type of input data will not have any difference on the fundamental design of the GIS evaluation process.

The research question is formulated as follows: *'To develop a method, based on GIS and Remote Sensing techniques that is able to monitor unusual effects on vegetation that could be associated with GM crops in The Netherlands.'*

Remote Sensing has proven to be a very useful tool for monitoring practices in general. The benefits are:

- Satellite images provide uniform and global coverage of the earth surface (instead of point measurements in the field);
- Satellite systems provide objective observations;
- Regular revisit times (ranging from several snapshots a day to once a month).

More specifically Remote Sensing is also suitable to monitor any development in the vegetation dynamics. It operates by measuring the reflected or emitted radiation from the earth surface, where after several indicators of vegetation monitoring can be derived, such as the surface albedo, surface temperature, vegetation index (NDVI, EVI), leave area index, biomass production, evapotranspiration, CO_2 flux, etc. There is also a large variety in satellite systems which produce the remote sensing images; each one with its own specific spatial, temporal and spectral resolution.

An inventory is performed regarding (i) the available vegetation indicators and their characteristics and (ii) the suitability of the available satellite systems for vegetation monitoring. Proposed is to start phase II of this research with a pilot study on vegetation monitoring using the following indicator and satellite system:

- The NDVI and EVI vegetation indices as they are relatively easy to measure, they are highly sensitive for vegetation changes and not influenced by other parameters, such as weather conditions.
- A multi-annual time series of MODIS images, MODIS has the highest resolution (250 m) of the freely available remote sensing images that have a daily revisit time. One of the main research topics is whether the 250 m resolution is high enough for the purpose of this study, or if a time series of higher resolution images is necessary to reveal more details at field level.

6 Outline phase II

In phase II of the research the first step of a GS, the 'observation of unusual effects on vegetation' (see section 2.1) is worked out in an operational monitoring system. Based on the recommendations of the first phase of this research, the second phase investigated the usability of NDVI - obtained from remote sensing images - time series to characterize vegetation dynamics or plant phenology. The EVI is not further investigated as for the method development and testing they are identical parameters, in the sense that they both are ratios between 0 and 1. The following steps can be distinguished within such a monitoring system:

1. Selection of remote sensing indicator(s)

The possible indicators are explained in section 3.5 and in section 3.6 it is concluded that the NDVI is the most suitable indicator to characterise the vegetation dynamics as it is easy to calculate and has the highest sensitivity to changes in the vegetation characteristics.

2. Selection and downloading of remote sensing images

The analysis is based upon multi-annual time series of MODIS images. MODIS has the highest resolution (250 m) of the freely available remote sensing images with a daily revisit time. MODIS has an additional advantage, since it also provides composite images from the 16-days-maximum-NDVI product. The 16-days-maximum-NDVI composite images have the advantage to exclude cloud affected data. Only when all 16 days in a composite are cloudy, the image is cloud affected. Unfortunately this is regular practice in The Netherlands, so screening is necessary to filter out the cloud affected data. Additionally, the 16-day composites use a mask to filter out the large surfaces of open water, like sea and lakes. This mask is known to be inconsistent, which makes the results near the shoreline (within 15 km) unreliable. In spite of the shortcomings of the composite images, the 16-days-maximum-NDVI product also saves a large amount of time in pre-processing and provides annually 23 images which is sufficient to be used in time series analyses. Therefore the NDVI composite product is downloaded and used during this research. In case the outcomes are not satisfactorily, it may be decided to exchange the 16-day composites by the original daily images.

3. Subsetting and georeferencing

The Netherlands will be encompassed completely. The years 2003, 2007 and 2008 are selected to be analysed. The year 2003 is selected because it was very dry with a relatively cold winter and 2007 and 2008 are selected as relatively wet and warm years.

4. Time series analysis

A time series analysis of the selected three years of NDVI images is needed for two reasons:

- To filter out and/or replace cloud affected or missing data in the input data;
- To quantify the vegetation dynamics over the year (start of growing season, peak and magnitude, end of growing season).

To meet the first requirement different interpolation techniques can be used, like moving average. The second requirement needs an analysis tool that is able to detect and quantify temporal changes in a uniform way for all raster cells. Ways to do this are using simple threshold values or more advanced harmonic components analysis, like wavelet of Fourier techniques.

HANTS combines both requirements in one algorithm and is unique in this way. It will be used for time series analysis of the NDVI composites of the MODIS satellite. Besides its ability to (i) exclude erroneous data and (ii) quantify the vegetation dynamics the use of HANTS has another advantage: (iii) compression of data; as the information of many input images is stored in a few resulting output images.

The HANTS algorithm is explained in more detail in Chapter 7.

5. Comparison between years

The HANTS results of different years are compared against each other, to see were major changes in vegetation phenology occurring. These changes are the result of external effect (like weather conditions, human interventions, GMO effects). Chapter 8 describes the comparison between years.

6. Analysis of outliers

Especially since the vegetation phenology in agricultural areas changes constantly, depending on the applied crop rotation scheme, a difference is made between natural and agricultural areas. The vegetation cover in natural areas is considered to be similar over the years and in principle is only influenced by the variation in weather conditions. However, always extreme outliers can be found, so-called ‘hot-spots’. These hot-spots will be analysed in detail, as they can be regarded as 'observations of unusual effects on vegetation', the main objective in this research. Areal photographs are used to zoom-in on the hot-spots to find a plausible explanation for the observed outlier. These plausible explanations are treated in the second part of Chapter 8.

7 HANTS time series analysis

The use of time series analysis on remote sensing images offers great opportunities for year-to-year monitoring of the earth surface. However, two serious drawbacks have to be dealt with, namely (i) time series analysis on remote sensing data produces huge amounts of data that needs to be processed and analysed and (ii) the presence of erroneous data, like cloud affected or missing pixels.

The selected HANTS (Harmonic ANalysis of Time Series) algorithm (Roerink et al., 2000) deals with the latter mentioned drawbacks pretty well, and has three major benefits:

- Large data reduction. The method allows reducing the amount of data by a factor of at least 5 without loss of information. In the example of Figure 8 the individual NDVI values from 36 decades are reduced into 5 HANTS components (3 amplitude and 2 phase values).
- Erroneous data exclusion. The method is able to exclude cloud affected and missing pixels in the analysis.
- Objective and quantitative characterisation of plant phenology (or vegetation dynamics). The time series of NDVI remote sensing images are described by the Fourier components (amplitude and phase).

Because of its benefits, HANTS has been used successfully for diverse applications, such as cloud screening, removal and replacement (Roerink et al., 2000), land cover classification (Zhang et al., 2008), plant phenology characterisation (White et al., 2009) and climate variability assessment (Roerink et al., 2003).

HANTS is a least squared curve fitting procedure, based on harmonic components (cosine-functions), and considers only the most significant frequencies expected to be present in the time profiles. In an iterative process, input data values that have a large positive or negative deviation from the current estimated curve are excluded from the procedure. This process is repeated until the maximum error is acceptable or the number of remaining values becomes too small. The entire curve fitting procedure is controlled by five parameters, which have to be set at the beginning of each HANTS run:

- Number Of Frequencies (NOF). A curve is described by mean of its average (frequency zero) and a number of cosine functions with different frequencies. By this control parameter the user defines how many cosine functions are used and what the frequency (time period) of each cosine function is. This results in 2 x NOF - 1 output parameters (an amplitude and phase value for each frequency), where NOF includes a frequency zero (time series average), which has no phase.
- High/Low Suppression Flag (SF). This flag indicates whether high or low values (outliers) should be rejected during curve fitting.
- Invalid Data Rejection Threshold (IDRT). In some cases one might know that digital numbers below or above a certain threshold should be considered invalid.
- Fit Error Tolerance (FET). During curve fitting the absolute difference in the Hi/Lo direction of the remaining (i.e. not rejected) data values with respect to the current curve is determined after each iteration. The iteration stops when the difference of all remaining values becomes smaller than the FET. The FET value should not be set too low, as otherwise the fit might be based on too few values, which gives unreliable results.
- Degree of OverDeterminedness (DOD). The number of valid observations must always be greater than or equal to the number of parameters that describe the curve (2 x NOF - 1). In order to get a more reliable fit the user can decide to use more data values than the necessary minimum. The minimum number of extra data values, which have to be used in the ultimate fit, is given by the DOD value.

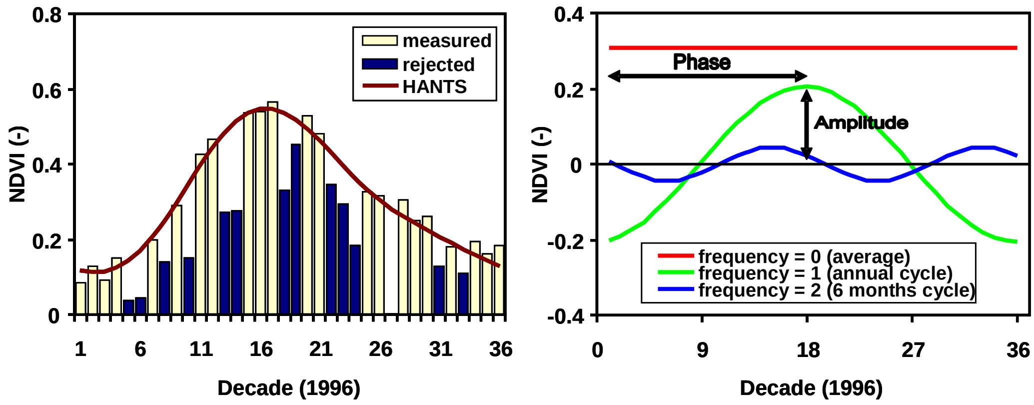

Figure 8

Visualisation of the HANTS algorithm (after Roeirnk et al., 2000)

The basic principle how HANTS works is visualised in Figure 8, where an original and HANTS reconstructed NDVI time series for a pixel of arable farming in Northern France are shown. The number of frequencies used by HANTS was set at 3: the average NDVI (frequency = 0), the yearly amplitude (frequency = 1) and the amplitude of 6 months (frequency = 2). The iteration stopped when 14 out of the 36 original NDVI values were rejected, i.e. classified as cloud affected data points. In this case, the remaining 22 values are allowed to have a maximum negative deviation from the curve of 0.05 NDVI units (=FET). The right graphs in Figure 8 shows the harmonic components of the 3 different frequencies, from which the cloud-free profile is reconstructed. Frequency zero (straight line) is represented only by amplitude and no off-set, while the other remaining frequencies (cosine functions) are defined by an amplitude and a phase value.

8 Results

8.1 Available data sets

Like already explained in chapter 6 (Outline phase II), MODIS 16-days-maximum-NDVI composite images are used to characterize vegetation dynamics over the years 2003, 2007 and 2008. To explain the differences between the different years, the following additional information sources are used:

- Meteorological data (recorded in meteorological station 'De Bilt');
- LGN (Netherlands land cover map);
- Aerial photographs of 2003 and 2006;
- Expert knowledge.

8.2 HANTS results

The curve fitting process is controlled by five control parameters, which have to be set at the beginning of each HANTS run (see Chapter 7). In the framework of this research the control parameters are set at:

- NOF = 3, where ;
  - Frequency 0: NDVI average;
  - Frequency 1: Phase and amplitude of the annual cosine function;
  - Frequency 2: Phase and amplitude of the six monthly cosine function.
- SF = Low; which means only low values (outliers) should be rejected during curve fitting, as they correspond to cloud affected data.
- IDRT = 0; as missing data in the original NDVI composites have a value 0.
- FET = 0.05; as the NDVI values ranges from 0 to 1, a FET of 0.05 means that 5% deviation from the fitted curve is tolerated.
- DOD = 8; the maximum number of data points that may be rejected is 10 out of 23 available values.

Since this HANTS operation includes three frequencies, the output will consist out of five images:

Image 1. The amplitude of frequency 0, which is the average NDVI value, or the average amount of vegetation over a year (frequency 0 has no phase as it is a constant value over the year, i.e. has no starting point).

Image 2. The amplitude of frequency 1, which reflects the seasonal vegetation difference between summer and winter.

Image 3. The phase of frequency 1, which describes when exactly the peak vegetation takes place.

Image 4. The amplitude of frequency 2, which is the amplitude of the 6 months cosine function. As in most cases vegetation dynamics have only one growing season during a year, the six months amplitude has no physical meaning like the annual amplitude, but is necessary for a smooth curve fitting procedure.

Image 5. The phase of frequency 2 which is phase of the 6 months cosine function; like the amplitude of the six months cosine function its physical meaning is limited, but is necessary for a smooth curve fitting procedure.

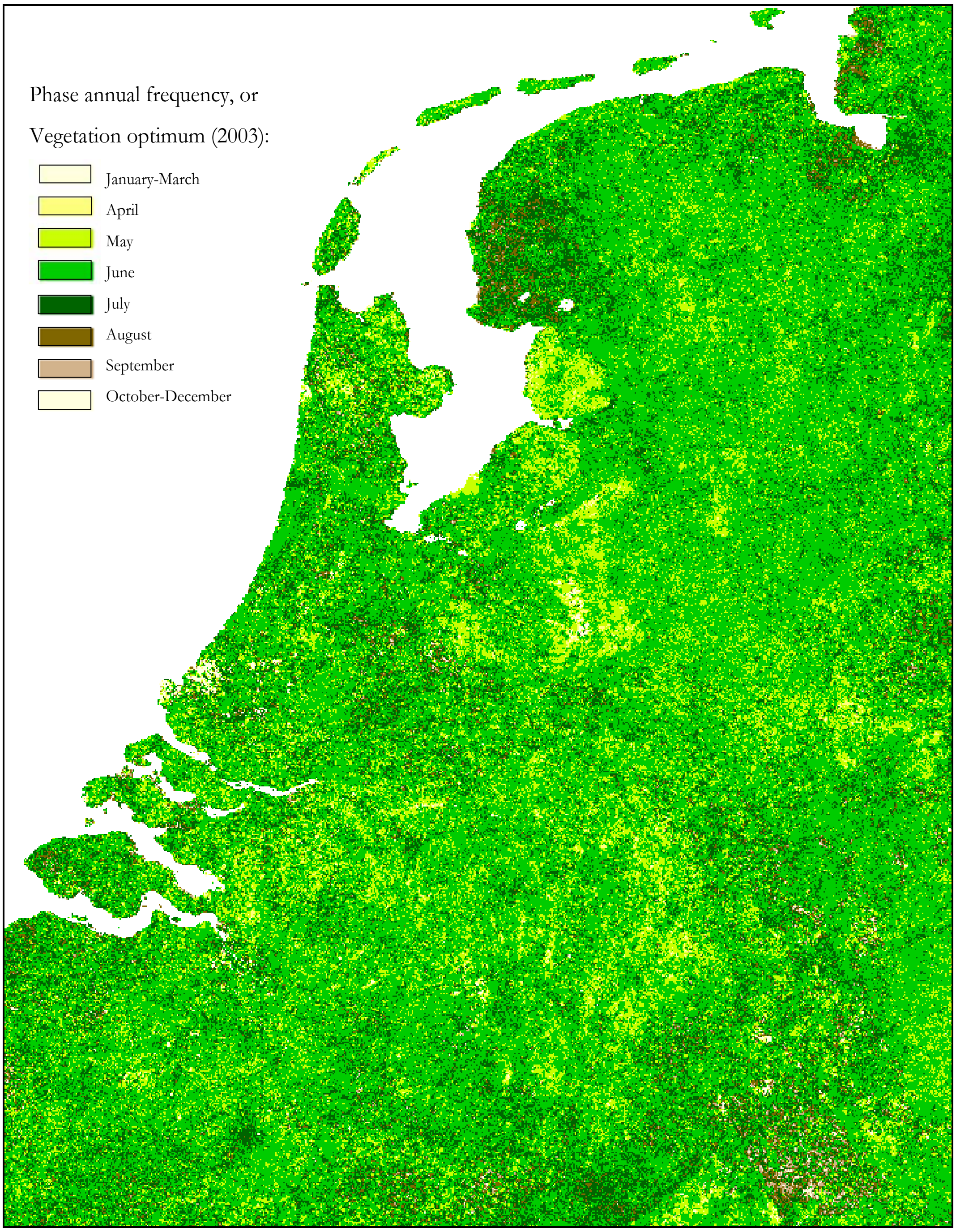

Figure 9
Map of vegetation optimum (= HANTS annual phase value)

Figure 9 and Figure 10 are visualisations of the HANTS results for the year 2003, where the first figure shows the phase of the annual frequency (as described at Image 3) by indicating the moment where the vegetation dynamics reach their optimum (maximum NDVI). It shows that there is a temporal and spatial difference in the optimum vegetation "greenness". In some cases this is related to the land cover, e.g. the Veluwe national park (nature conservation in the centre of The Netherlands) is clearly visible due to the coniferous forest and heath lands.

Figure 10
False colour composite image of the HANTS results of the year 2003, where red = NDVI average; green = amplitude of annual frequency; blue = amplitude of the six months frequency. The numbers refer to the graphs in ***Figure 11***

In Figure 10 the three resulting amplitude images are combined in a false colour composite image, where the red colour represents the average NDVI (frequency 0), the green colour represents the amplitude of the annual frequency and blue represents the amplitude of the six months frequency. So a bright red colour means a large amount of vegetation throughout the year, but no seasonal effects, e.g. pastures or pine forests. Green colours represent a strong seasonal effect, like for example arable farming. Yellow, being a combination of red and green, represents for example deciduous forest, which in summer has in summer high vegetation values, but also a annual growing cycle. The dark spots have low amplitude values in all three frequencies, so contains no vegetation throughout the year, like bare soil or urban areas.

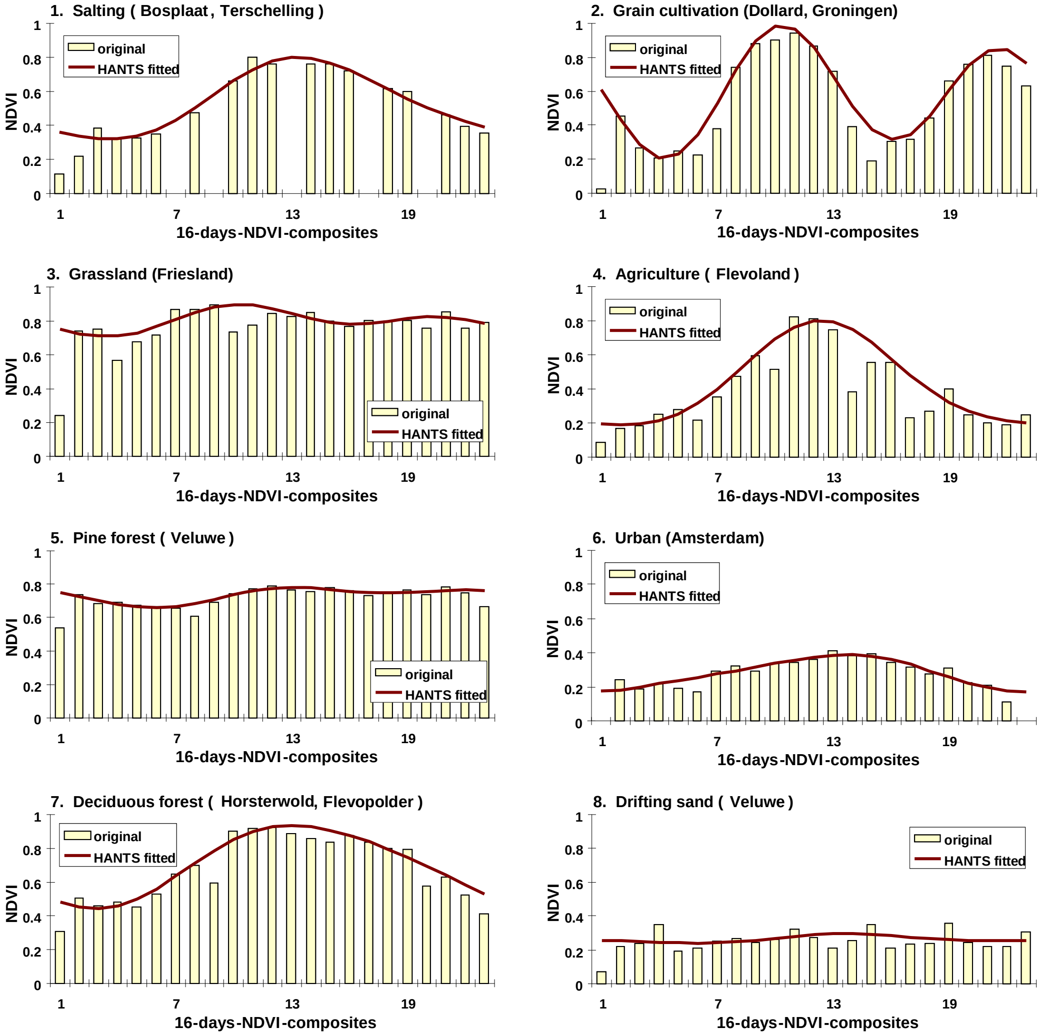

Figure 11

Yearly profiles of original NDVI values and the HANTS fitted curve of typical land cover types in the Netherlands. The locations are indicates in Figure 10

The temporal behaviour of NDVI time series is discussed in detail for 8 typical land cover types in the Netherlands in Figure 11. The locations of the land cover types are indicated in Figure 10. As explained in section 3.5, bare soil has an NDVI of around 0.2, whereas vegetation scores a value between 0.7 and 0.9. Due to the annual climatic cycle, the NDVI is lower in the winter than in the summer. However, a large amount of information can be obtained from average NDVI, the annual amplitude and the lowest NDVI. For example the NDVI for arable farming is around 0.2 during winter time, since the soil is ploughed or cultivated (see graph 2 and 4 in Figure 11). In the case of granary area 'De Dollard' (graph 2 in the North of The Netherlands), there are two cultivations a year, first the cereals, and later on in the year a fertilizing crop. It is one of the few cases in the Netherlands that the six months frequency has a physical meaning. Natural areas are not cultivated, so they will never score an NDVI value of bare soil as also in winter some shrubs and grasses are visible (graph 8). However, even between natural habitats there is a strong deviation in the height of the NDVI during the winter. For example pastures (graph 3) and pine forests (graph 5) remain green throughout the year, which result in a small annual amplitude and a high NDVI average. Deciduous forest (graph 7) and shrubs (graph 1) on the other hand, loose their leaves, which result in a larger annual amplitude compared to pastures and pine forests but lower than agriculture. Finally, urban areas have a very typical NDVI dynamic (graph 6). The majority of the surface in cities is covered with concrete, brick or asphalt. This results in a low and stable NDVI.

However, in every city there are trees, parks and gardens, which results in a small NDVI increase during the summer.

8.3 Comparison between years

HANTS is applied on all three years of NDVI composites. This makes it possible to compare the results of different years to each other. As only three years were analysed only the difference between them is studied. An example is shown in Figure 12 where the NDVI averages (HANTS result from frequency 0) of the different years are subtracted form each other. It is clear that 2007 and 2008 have in general higher values than 2003 and that 2008 has lower values than 2007. This corresponds well to the temperature and precipitation sums of these years (Figure 13). The precipitation in 2003 was much lower than in the other two years, so lower vegetation values can be expected.

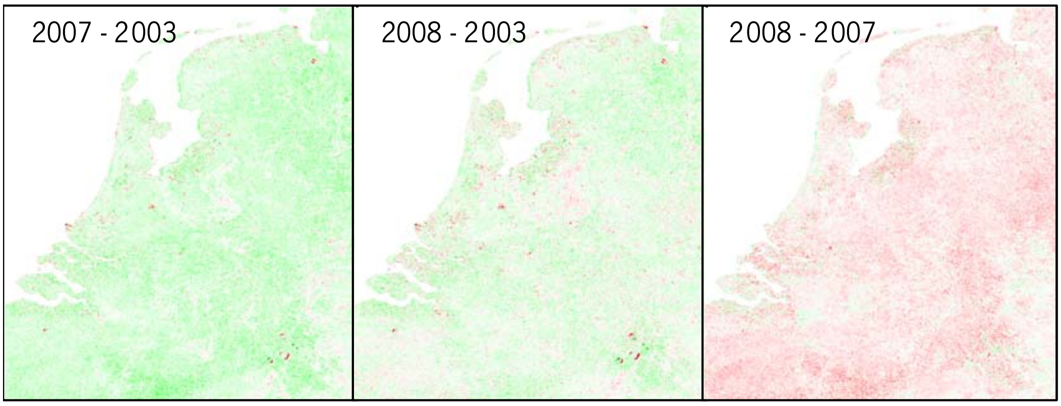

Figure 12
Average NDVI images of different years, subtracted from each other (green: the first year has higher values than the last year; red: the first year has lower values than the last year)

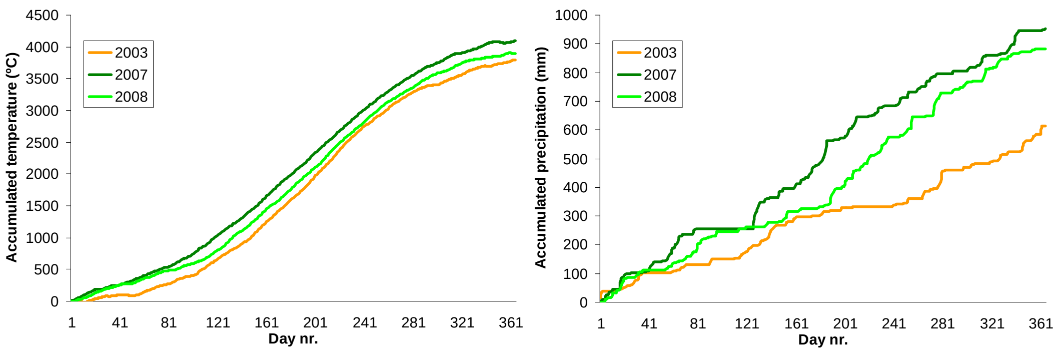

Figure 13
Accumulated temperature (left) and precipitation (right) sums of meteorological station De Bilt in the Netherlands over the years 2003, 2007 and 2008

Based on the HANTS results of the different years it is now also possible to calculate the average annual NDVI profile of the Netherlands, i.e. the average is taken from all the pixels in The Netherlands image. The resulting NDVI profiles are shown in Figure 14. It characterises the vegetation dynamics in relation to the weather conditions in a particular year very well. Where 2007 and 2008 resemble a lot, the profile of the year 2003 differs. The differences in 2003 can be explained by its relatively cold winter and dry summer; both events in the NDVI profile can be observed as dips in the curve.

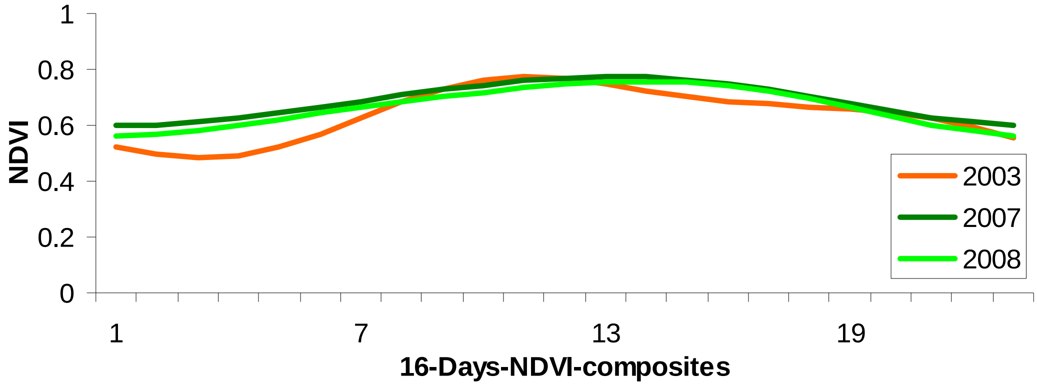

Figure 14
Average annual NDVI profiles of the Netherlands from 2003, 2007 and 2008, as derived from the HANTS analysis

8.4 Unusual effects on vegetation

The main question in this research is not how vegetation responds to climate variability, or to observe and quantify expected (or usual) effects on vegetation, but the opposite, how to observe unusual effects on vegetation. This section shows that the HANTS results are suited for such a purpose as well. Nevertheless, some additional steps remain necessary.

Unusual effects on vegetation are defined in this study as the most extreme differences between the HANTS results from different years. For example a forest fire has an extreme unusual and unexpected effect on vegetation. Problem is that similar extreme differences occur when farmers change their cropping patterns on their fields over the years; however, changing cropping patterns is a usual and expected effect of arable vegetation. Since at this stage the objective of this research is to explore the possibility for detection of unusual effects, agriculture is for the time being excluded and only natural areas are further elaborated. The natural areas are obtained by using the LGN land cover map of The Netherlands. Figure 15 shows only the land cover classes belonging to the category nature.

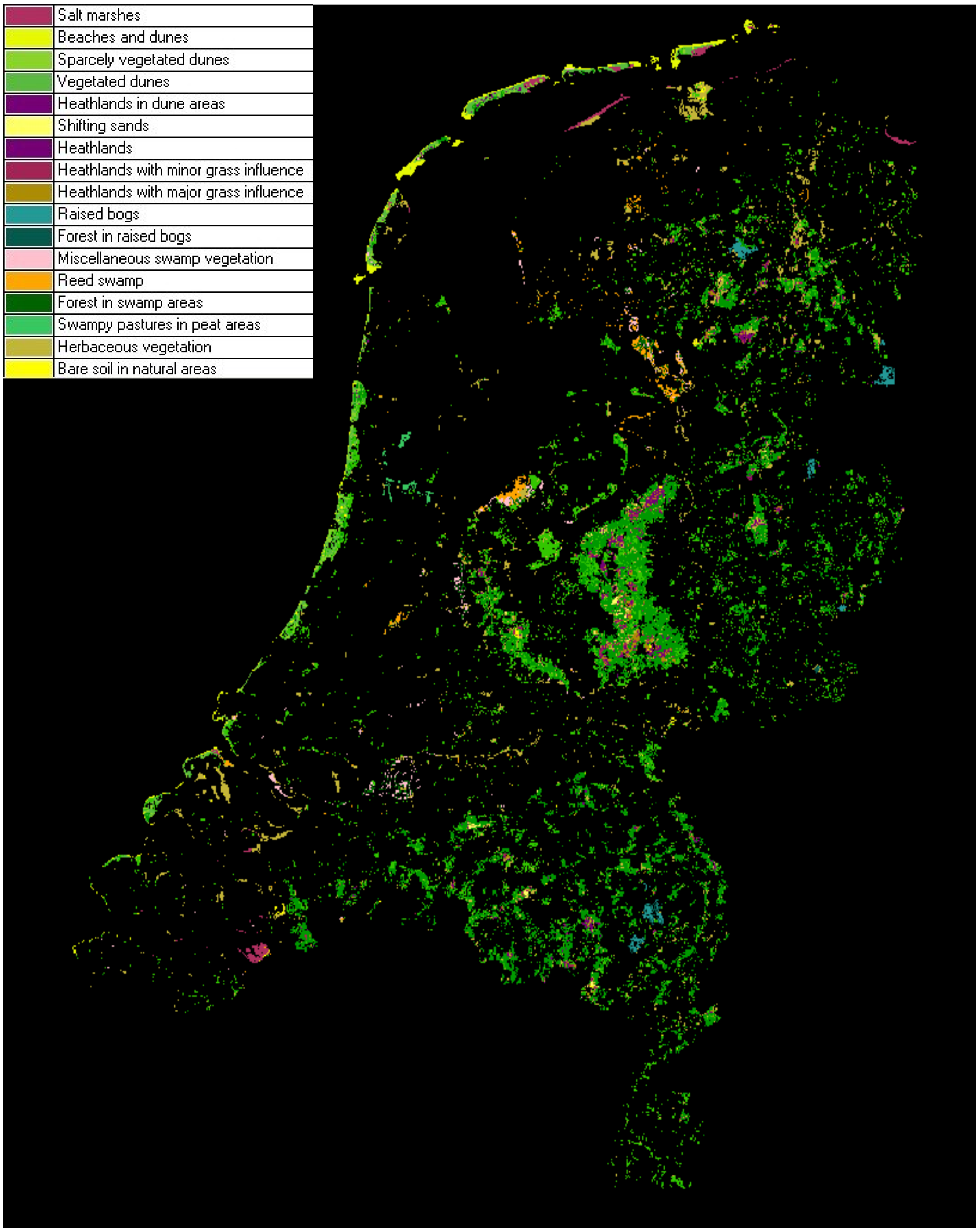

Figure 15
Natural areas in the LGN land cover map of the Netherlands

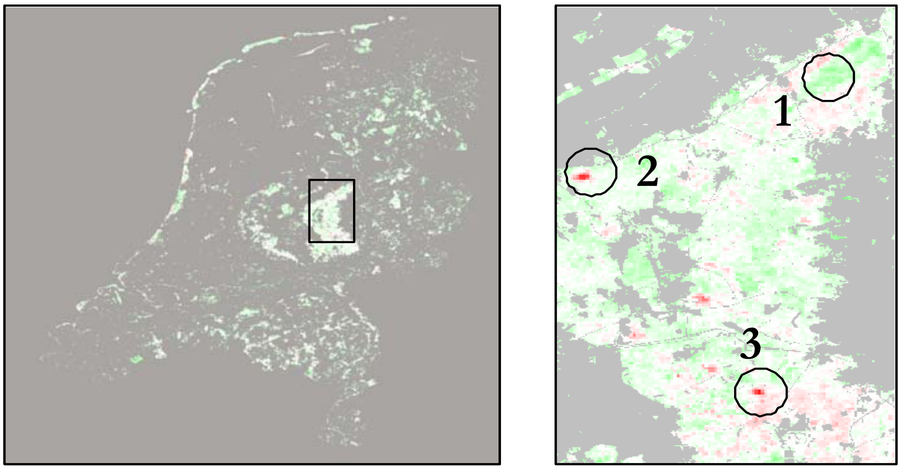

Figure 16a

Map of average NDVI of 2007 minus 2003 (green: 2007 has higher values that 2003; red: 2003 has higher values than 2007) with the location selected hot-spots in the Veluwe national park (up heath to grass, muddle heath removal, below pine forest to heat)

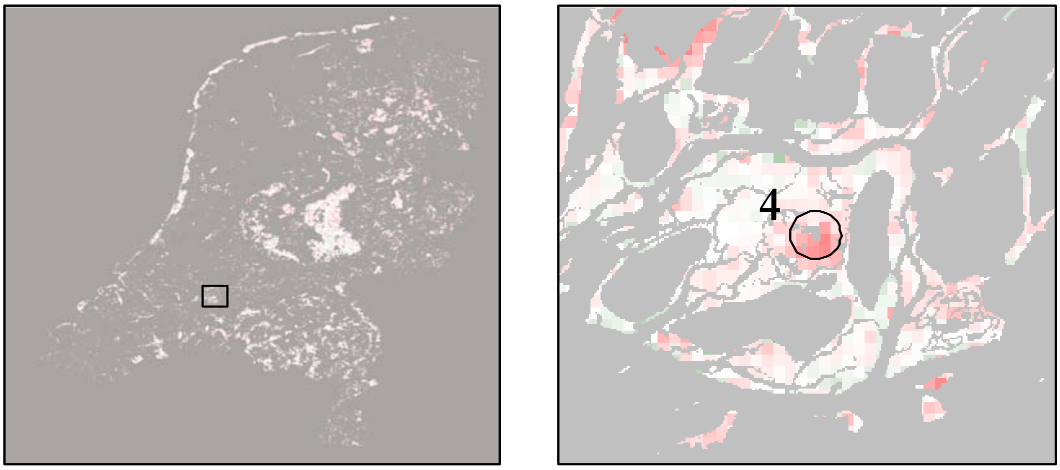

Figure 16b

Map of annual amplitude of 2007 minus 2003 (green: 2007 has higher values that 2003; red: 2003 has higher values than 2007) with the location the selected hot-spot in the Biesbosch wetlands

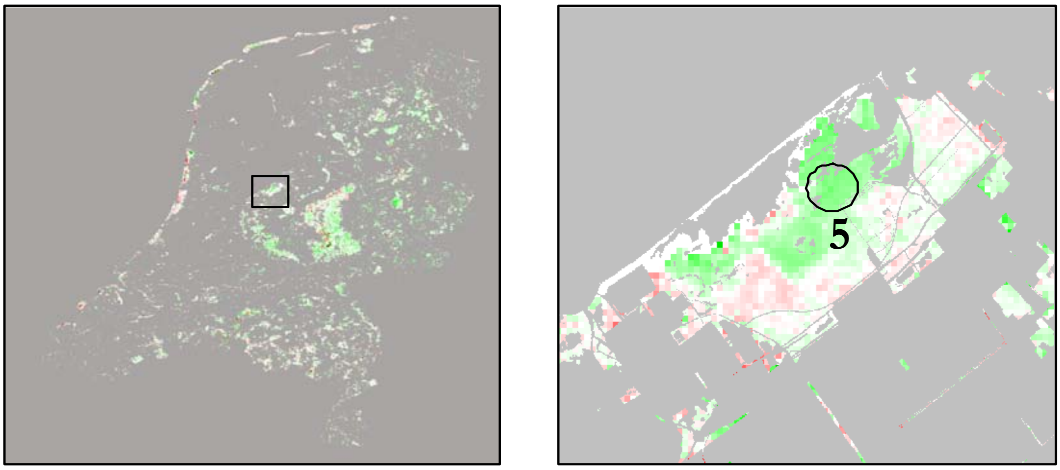

Figure 16c

Map of annual phase of 2007 minus 2003 (green: 2007 has earlier vegetation peak that 2003; red: 2003 has earlier vegetation peak than 2007) with the location the selected hot-spot in the Oostvaardersplassen

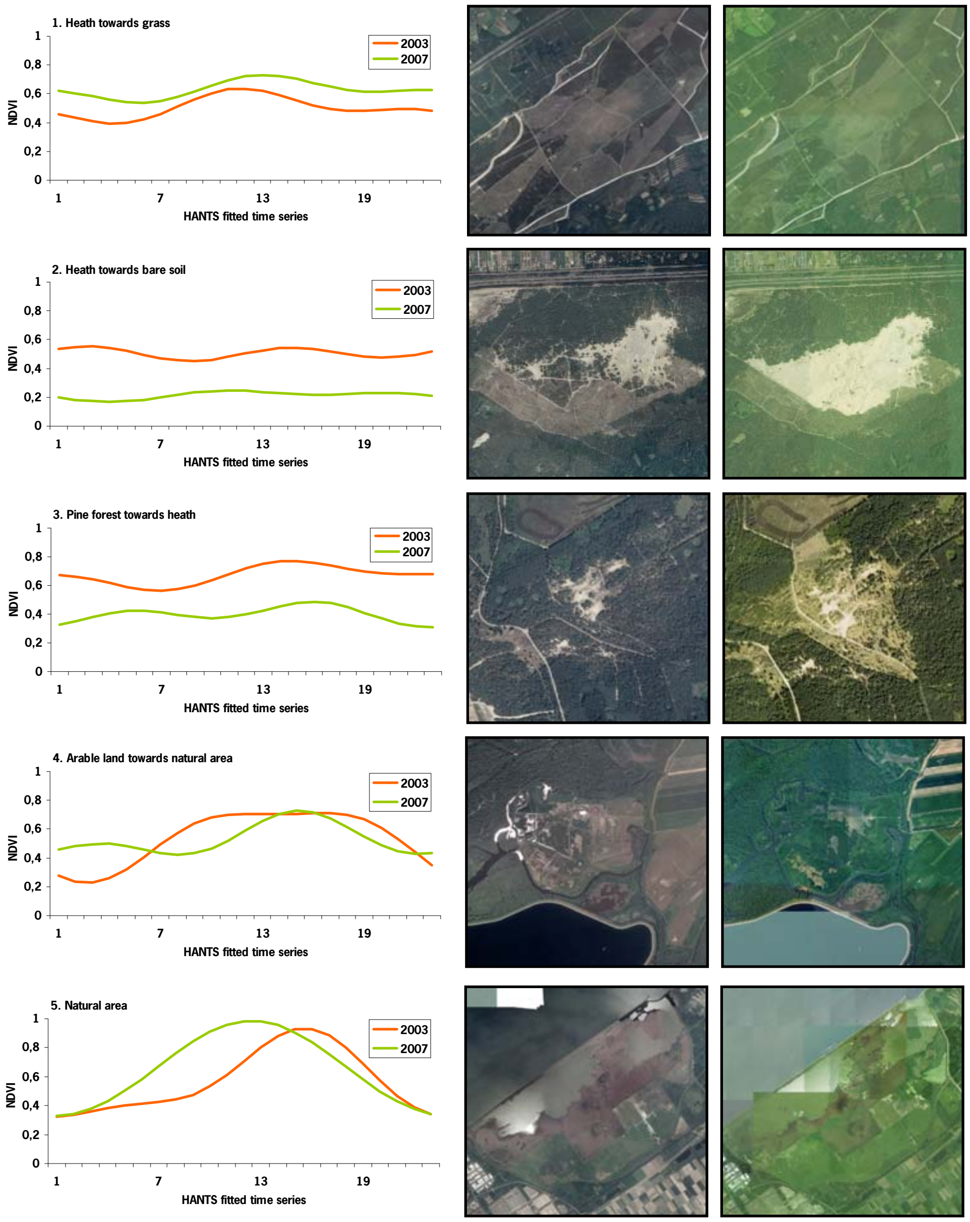

Figure 17
Temporal NDVI profile of hot-spots of unusual effect on vegetation and corresponding aerial photographs from 2003 (left pictures) and 2006 (right pictures). The locations are indicates in Figure 16

After masking all land-use classes except nature, it becomes possible to zoom-in on extreme vegetation phenology differences between years. Figure 16 and Figure 17 show five different areas, or so-called 'hot-spots', where there is an extreme difference between the HANTS components from the different years. These hot-spots are located in the Veluwe national park (three hot-spots), the Biesbosch wetlands and the Oostvaardersplassen national park, all relatively large natural areas in The Netherlands. After identifying the hot-spots, it is attempted to find a plausible explanation for the unusual change of vegetation phenology, by analyzing higher resolution aerial photographs that originate from 2003 and 2006 in combination with the LGN land cover map.

The first three hot-spots are located in the Veluwe national park, a large nature area on high sandy soils covered with shifting sands, heath and forest. The hot-spots are selected for their extreme differences between the average NDVI from 2003 and 2007. In two cases the average NDVI in 2003 was higher than 2007 and in the remaining case the opposite happened. Looking at the aerial photographs they reveal clearly that human intervention is the cause for the sudden change of average NDVI values. It concerns activities in nature conservation such as heath removal from drifting sands and the cutting of pine trees. For the hotspot where the average NDVI in 2007 was higher than 2003, it is harder to find a plausible cause. From the aerial photographs it becomes clear that there are no human interventions, in contrast to the other cases. However, from the LGN land cover map it becomes clear that the land cover is heath, which is sensitive for increasing succession when intervention activities lack, e.g. grazing by sheep.

The fourth hotspot is located in the Biesbosch wetlands in the delta area of the large rivers in the Netherlands. Here the extreme difference in annual amplitude was the base to identify it as hot-spot (note that the average NDVI value of both years is more or less the same). Visual inspection of the aerial photographs doesn't reveal a simple explanation. However, looking at the 2003 NDVI curve in Figure 17, the minimum is about 0.2, and knowing that this value only occurs to bare soil, it should be ploughed land, or in other words arable land. In 2007 the minimum value was about 0.4, which does not belong to bare soil anymore. One comes to the hypothesis that this piece of land is changing from arable land to nature. Browsing the internet revealed that indeed in the period from 2005 onwards polders in the Biesbosch are turned into wetlands again (www.dezuiderklip.nl).

The fifth and final hot-spot is located in the Oostvaardersplassen national park, located in the lowest wet part of the Flevopolder covered with lakes, pastures, reed and forest. The hot-spot is identified on basis of an extreme shift in annual phase value. As one can see the average NDVI and also the annual amplitude are more or less the same. The aerial photographs reveal no special details and so far no plausible explanation can be given for the shift in peak vegetation from about September in 2003 to about July in 2007. Here a truly unusual effect on vegetation is identified and a more in-depth study may be necessary.

9 Discussion

Based on the analysis one might conclude that the described HANTS method works fine for the identification of unusual effect on vegetation; however, still some critical remarks can be made. First of the all quality of the input remote sensing imagery can be discussed and second, the sensitivity and accuracy of the developed monitoring method for general surveillance should be evaluated.

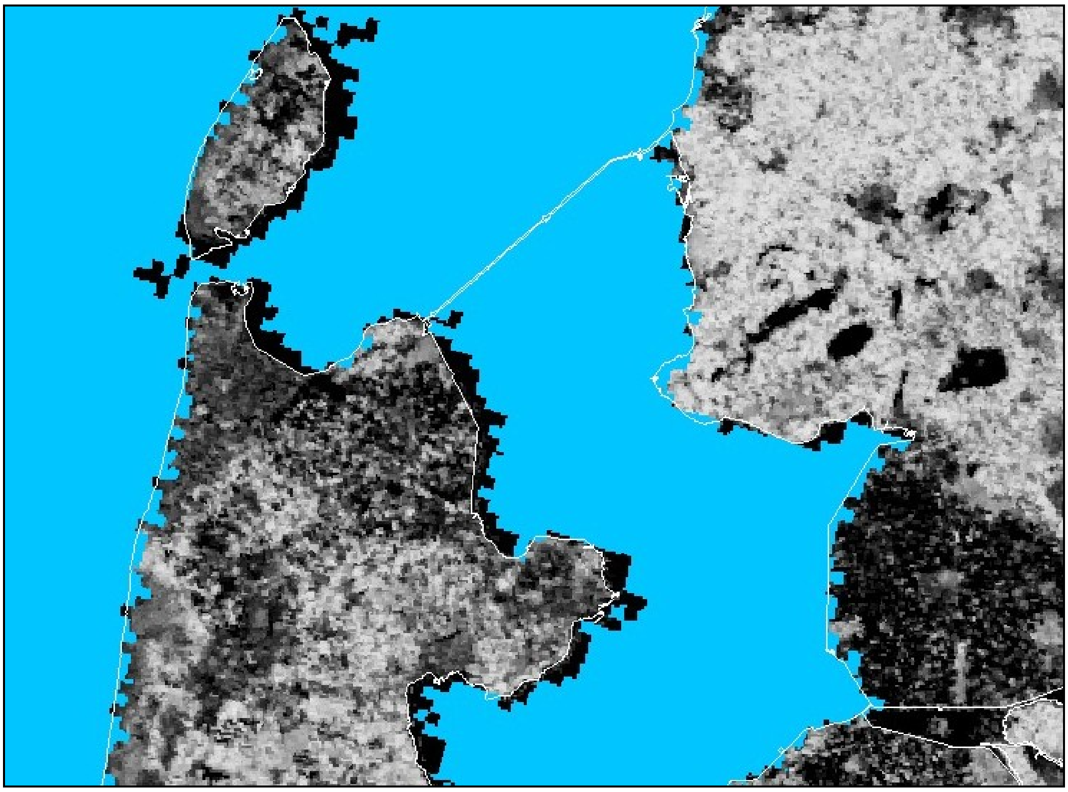

Figure 18
Problematic water masking of MODIS 16-days-maximum-NDVI-composites (blue areas are masked as water)

9.1 Quality of the input data

Water masking procedure
The general remark 'what comes in, goes out' is also applicable during this research; the quality of the results depends totally of the quality of the input data. In this research the input data are 16-days-maximum-NDVI-composites, which are in general of excellent quality.

However, there is one serious problem related to the composites, which concerns the masking of water bodies. This automatic water masking procedure is not very accurate and sometimes excludes also coastal areas. In this way a maximum of about 10 to 15 pixels (~3 to 4 km) near the shoreline can be masked as water (see Figure 18). Remarkably, the masking is only incorrect for shorelines that border east from water. Consequently, strange effects in HANTS curve fitting occur frequently, due to missing NDVI values. To overcome this issue, one could choose to use the daily images instead of the 16-days composites. These daily images do not have a water mask; however, the use of daily images will take far more processing time.

Length of time series

It is recommended to study a longer period than the three years this study is currently based on. Based on long-year averages it should be possible to establish a kind of baseline. Once the baseline is set, near real-time monitoring might become possible as well. MODIS satellite images are available from 2000 onwards.

9.2 Spatial resolution

The MODIS input images used here and therefore also the resulting HANTS outcomes are limited to a resolution of 250 m. This is not sufficient to detect changes at field level, especially given the relative small parcel sizes and heterogeneous land cover in the Netherlands. To detect changes within small natural areas or agricultural plots, a resolution of 30 m or higher is necessary. However, to apply the same analysis to, for example, RapidEye satellite images (5 m resolution) are rather expensive, processing intensive and produce such large amounts of data that it becomes practically impossible to apply it on a scale of the Netherlands or Europe.

The 250 m resolution of MODIS is small enough to detect changes within natural areas, like the Veluwe national park, Biesbosch wetlands or Oostvaardersplassen national park. A moderate resolution allows making a relative quick analysis, covering the extent of The Netherlands or even Europe and can therefore be regarded a suitable data source for starting-up the developments in the realm of General Surveillance. When unusual effect on vegetation are detected, which cannot be explained sufficiently, one might choose for a detailed local study with multi-temporal high resolution data.

9.3 Suitability for General Surveillance

The basic objective of this research is to develop a method for General Surveillance of unanticipated adverse GMO effects on vegetation. Initially the to-be-developed GS method should be able to:

- Observe unusual effects on a national scale;
- Determine whether unusual effects are adverse;
- Determine whether the adverse effects can be associated with the GMOs and not with other aspects that origin from a dynamic agro-environment.

As explained in the previous chapters, the focus of this research was on the first sub-question. The developed monitoring method in Chapter 8, based on the HANTS analysis of NDVI satellite images, is able to discriminate unusual effects on vegetation in natural areas in a quantitative way, so the first sub-question can be answered positive if the monitoring is restricted to natural areas.

The second sub-question, determinating whether unusual effects are adverse, is not taken into account in this research, as all unusual effects (positive and negative) are in this stage relevant to be further investigated whether or not they can be associated with GMOs, which is the third sub-question.

So far the third sub-question cannot be investigated fully, since at this moment (year 2009) no GM crops are commercially cultivated in The Netherlands. So by definition the currently observed changes in vegetation phenology cannot be not associated with GM crop cultivation. However, the third sub-question can be broadened and reformulated as follows; 'how can unusual effects on vegetation phenology be explained by whatever cause'. Additional information is always necessary to answer this question. In this research aerial photography and expert knowledge is used to explain in more detail the observed phenomena and plausible causes can be indentified, like for example, forest cutting, giving arable lands back to nature and increased grass growing in heath land. Using this approach it is possible to explain most of the example hot-spots. The hypothesis is that with additional information sources almost all unusual effects can be explained and that the remaining effects are reported as unidentified effects. These unidentified effects should be elaborated in a more in-depth study to see whether they can be associated to the cultivation of GMOs. An alternative approach is that the areas where unexpected effects are found are compared with the locations where GM crops are (or have been) cultivated, using GIS to see if there is a correlation. Also, both approaches could be combined.

Nevertheless this study introduces a promising method that may be used to answer the first sub-question in a GS. However, the question remains open if any GMO induced (unusual) effects (i) can be detected by the HANTS method, as described in this report, and if so, (ii) which information sources (if exist at all) can be used to verify/associate the observed changes to the cultivation of GMOs?

The first question can only be answered once the commercially cultivation of GM crops is taking place and induced unusual effects appear. However, what can be stated already is that the developed method is indeed sensitive in a quantitatively manner to annual changes in vegetation phenology. So, one might expect that any unusual effect of GMOs on the vegetation dynamics in natural areas will be detected by the developed HANTS method, as described in this report. However, one important note should be made regarding the magnitude of a GMO induced unusual effect on vegetation. In Chapter 8 the focus lies on so-called hot-spots, i.e. the most extreme HANTS differences between the selected pilot years. However, it might be very well the case that a GMO induced unusual vegetation effect are too small (at least in first instance) and not be as explicitly visible as the described hot-spots (see Figure 16). If this is the case, it is not possible to distinguish GMO associated effects from any ordinary annual changes in vegetation phenology in natural areas, without the help of additional information sources.

This brings up a second question. Assuming it is possible to detect GMO induced unusual effects on vegetation, how can they be verified, or at least be associated to the cultivation of GMOs? Again this question points out that complementary information sources might be necessary. For example information about the located GMO cultivations could be very valuable. Fortunately, in the Netherlands GM crop cultivation has to be registered formally. Furthermore additional GIS layers, like mentioned in section 4.2 and 4.3, and expert knowledge might be necessary to link unusual effect on vegetation to GMOs.

9.4 Differentiation within natural land cover types

Within the framework of this research natural areas have been treated as one land cover type and only the most extreme differences within the natural areas were selected and further analysed. This excludes the fact that natural areas cover a wide variety of land cover types (see Figure 15), which will react differently to external impacts as climate variability, human activities or GMOs. Therefore an analysis per land cover class is necessary.

9.5 Nature versus agriculture

The currently described method is only able to monitor natural areas, as arable farming induces each year major changes in vegetation phenology and therefore is always classified as ‘extreme’ changes in vegetation. The GS in principle requests that also agricultural areas are monitored, so a similar method could be developed for that purpose as well. A way to deal with agricultural areas might be to look at averaged temporal NDVI profiles of specific agricultural crops within larger regional units (municipalities, provinces, etc.) instead of evaluating individual pixels. By doing so the averaged temporal NDVI profiles, describing the crop phenology for each year and specific regional unit, can be quantitatively compared and analysed again. Additional information sources on the exact location of a specific crop within the larger regional units are necessary.

Such information sources could be the LGN land cover map of the BRP parcel registration (see also section 4.2). Also the GS approach based on farmer questionnaires could help in this respect.

10 Conclusions

According EU legislation a General Surveillance (GS) is necessary *'to monitor for unanticipated adverse effects of genetically modified organisms (GMOs) on human health and the environment'* (Lecoq et al., 2007) for importing and cultivating GMOs. Since unanticipated adverse effects can mean anything anywhere, many EU member states are struggling with their design of a GS. Remote sensing was identified as one of the possible information sources for such a GS, as satellite images provide objective and regular information of the land surface with complete nationwide coverage.

The objective of this research was formulated as '*To develop a method, based on GIS and Remote Sensing techniques, that is able to monitor unusual effects on vegetation that could be associated with GM crops in The Netherlands.*'

Phase I revealed that Remote Sensing is suitable to monitor any development in the vegetation dynamics. It operates by measuring the reflected or emitted radiation from the earth surface, where after several indicators of vegetation monitoring can be derived. The NDVI vegetation index is selected as best performing indicator, as it is relatively easy to measure, highly sensitive for vegetation changes and robust. There is also a large variety in satellite systems which produce the remote sensing images; each one with its own specific spatial, temporal and spectral resolution. The MODIS satellite system is selected for this research, as it has the highest resolution (250 m) of the freely available remote sensing images that have a daily revisit time.

In Phase II of this research a method is developed to monitor any unusual effect on vegetation in the Netherlands for natural areas only. First of all the vegetation dynamics are objectively quantified by a time series analysis of satellite images. Hereafter, the agricultural areas were masked, because they have changing vegetation patterns over the years due to their changing cropping system by definition. Ultimately the most extreme changes in natural areas over the years were identified as hot-spots. These hot-spots were analysed in detail with aerial photographs, land cover information and expert knowledge to come to a plausible explanation for the extreme changes in vegetation dynamics. In the cases where the cause of the change could not be discovered, the hot-spot was defined as an observation of an unusual effect on vegetation.

The developed method was applied to three years of 16-days-maximum-NDVI composites of the MODIS satellite, to be known 2003 (relatively dry and a cold winter) and 2007 and 2008 (both relatively wet). The HANTS algorithm was used to perform a time series analysis on the NDVI images. The temporal NDVI profile is characterised by the average NDVI and cosine functions one year and six months. In an iterative process the erroneous outliers (cloud affected and missing data) are rejected. In this way an objective and quantitative characterisation of the vegetation dynamics is performed, which makes it possible to analyse the results of the different years among each other. It can be concluded that there is a strong correlation between the calculated temporal NDVI profiles of the vegetation dynamics and the precipitation and temperature sums of the specific years.

Looking at the most extreme differences between the years, it can be concluded that this method is able to monitor any unusual effect on vegetation, limited to natural areas. Not only differences in the average amount of vegetation between the years forms the basis of the analysis, also differences in seasonal changes (annual amplitude) and differences starting of the growing season or peak vegetation (annual phase) are detected and quantified.

Five hot-spots in natural areas were analysed in detail and it was attempted to find a plausible explanation for the unusual effect on vegetation, by looking at higher resolution to the hot-spots with aerial photographs from 2003 and 2006 in combination with the LGN land cover map. For three areas the cause of the unusual effect were human interventions, another one could be explained by a natural process. However the last one, a shift of the growing season in time, could not be explained so far, and could be defined as an observation of a truly unusual effect on vegetation.

The MODIS input images and therefore also the resulting HANTS outcomes have a resolution of 250 m. This is not sufficient to detect changes at field level in agricultural areas, especially given the relative small parcel sizes and heterogeneous land cover in the Netherlands. However, the resolution is high enough to detect changes within natural areas, like the Veluwe national park, Biesbosch wetlands or Oostvaardersplassen national park. The moderate resolution allows making a relative quick analysis, covering the extent of The Netherlands or even Europe and may therefore be suited to start-up an operational framework for a General Surveillance.

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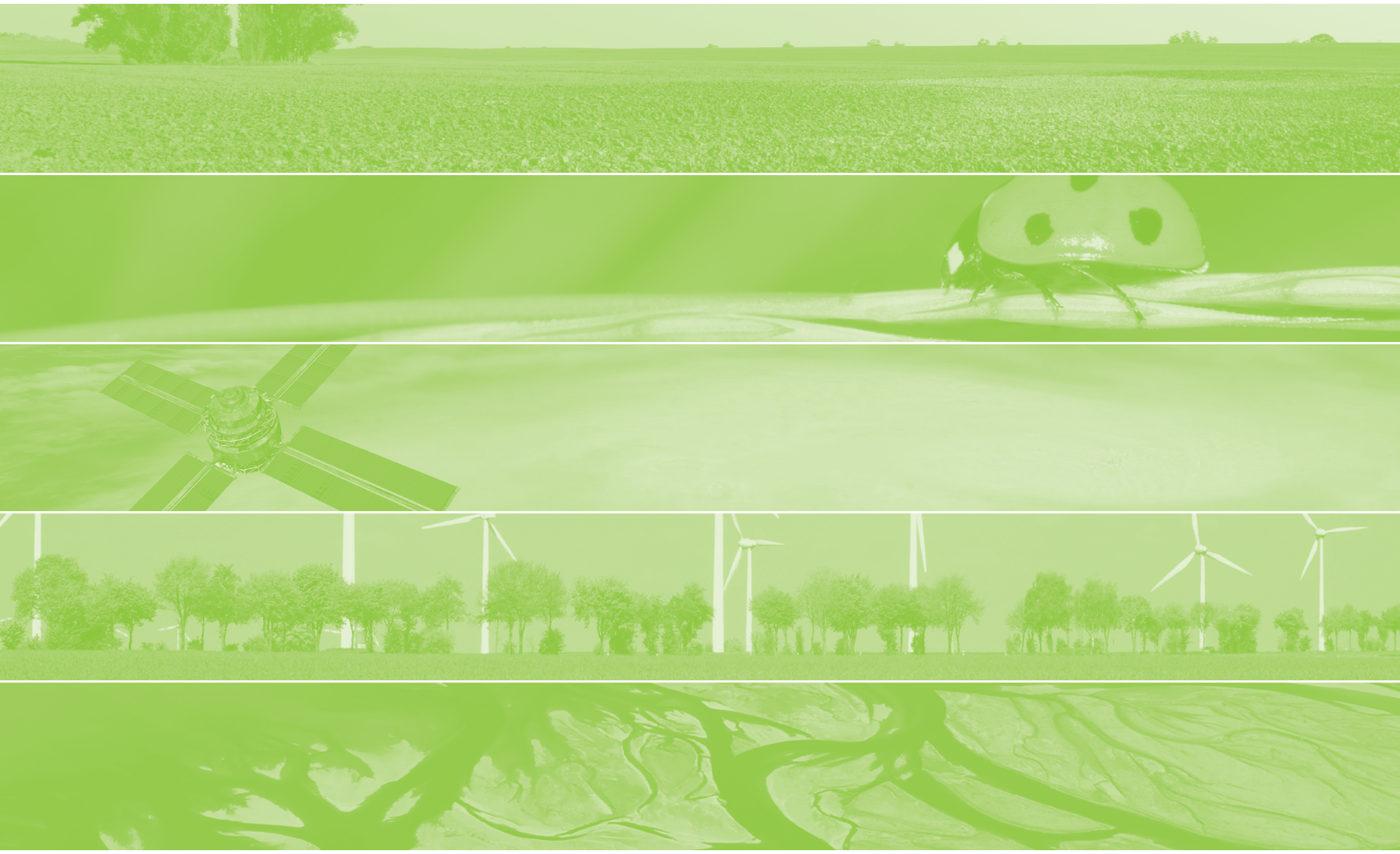

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