Final project report

Project acronym	**DIARS**
Project title	**D**etection of **I**nvasive plant species and **A**ssessment of their impact on ecosystem properties through **R**emote **S**ensing
Coordinator of the project (company/organization)	Flemish Institute for Technological Research (VITO)
Project coordinator (Name)	Ruben Van De Kerchove (he replaced Ben Somers)
Project period (Start date – End date)	01/01/2014 – 15/05/2018
Project website, if applicable	http://diars.vgt.vito.be/

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1. Short description for publicity

The biodiversity conservation policy of the European Commission includes the development of warning and rapid response systems for biological invasions and urges further investigations of their impacts on ecosystem function and services. However, using solely field-based approaches to mapping non-native invasive plant species distribution and their impact across landscapes is a time-consuming process and potentially subject to observation bias. Remote sensing provides a systematic, objective and synoptic view on Earth cover. Hence, this technique offers a great opportunity to target biological invasion and their impact across various spatial and temporal scales. Despite a handful studies – all of them outside Europe – that have followed a remote sensing approach, the use of remote sensing for studying biological invasions is largely underexplored and underused by invasion biologists. In response to this research need, the DIARS project (funded under the FP7, ERA-NET, BiodivERsA programme) has brought together European specialists from both remote sensing as well

as ecology. By focusing on three different plant life forms (Fig. 1) – a bryophyte species (*Campylopus introflexus*), a shrub species (*Rosa rugosa*) and a tree species (*Prunus serotina*) – occurring as non-native invasive plants in two contrasting ecosystems in Europe – dune habitats in Flanders (Belgium) and on the island of Sylt (Germany) as well as forest stands in the state forest of Compiègne (France) – the DIARS project provides guidelines and tools to assess (i) the distribution and spread of non-native invasive plants as well as (ii) the impact on ecosystem functioning through the combined use of field data and data obtained from airborne remote-sensing technologies (LiDAR and hyperspectral images) (Fig. 2).

Figure 1: Close-up of the three studied non-native plant invaders.
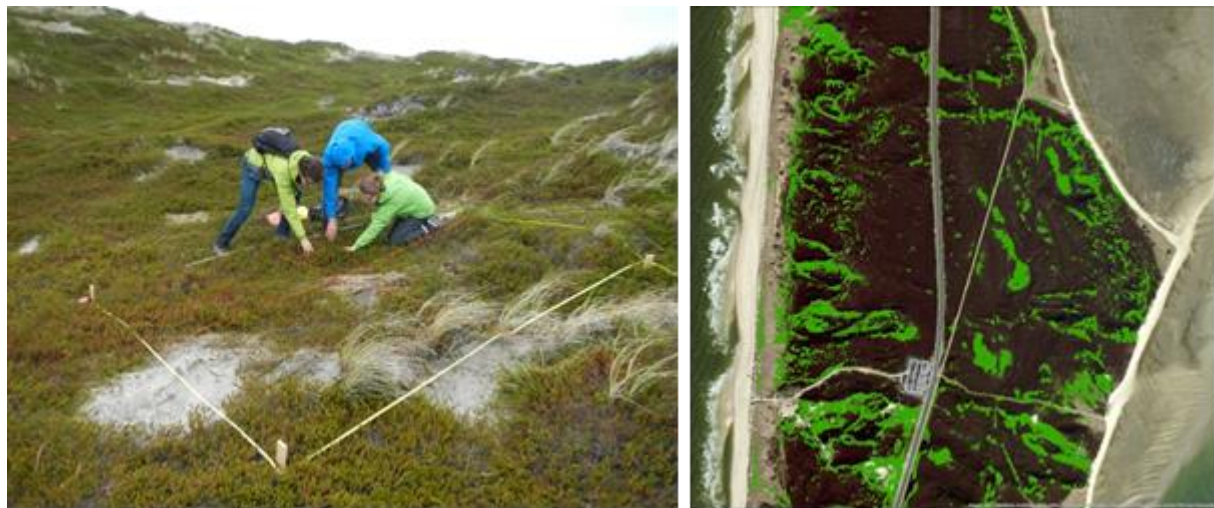

Figure 2: Sampling campaign (left panel) on the island of Sylt (DE) to detect and map (right panel), throughout the use of hyperspectral images, the distribution of *Campylopus introflexus*, a non-native and inconspicuous moss species occurring on the island.

2. Summary

One of the key findings of the DIARS project is to show the ability of airborne remote sensing data and more specifically hyperspectral remote sensing data to generate, in combination with field data, reliable distribution maps of *Campylopus introflexus* (Figs. 1 and 2), a non-native invasive moss species highly invasive in European dune landscapes. With this important finding, the DIARS project illustrates the potential of hyperspectral images to face the challenge of detecting small-stature invasive plant species like small and inconspicuous moss species and thus provide an alternative to traditional and time-consuming field mapping approaches over large areas.

Not only we need to provide tools to remotely map the actual distribution of a non-native invasive and inconspicuous species, but it is also needed to model its potential spread across the ecosystem. Unfortunately, the non-equilibrium distribution of invasive species with the environment within the invaded range affects the environmental representativeness of species presence-absence data collected from the field and introduces uncertainty in the observed absences as these may either reflect unsuitable sites or be incidental. Because of that, a blind use of absence data in species

distribution models (SDMs), which is the state-of-the-art to project the potential spread of an invasive species, is highly problematic. To address this challenge, the DIARS team has developed a novel modelling framework to carefully separate the absences reflecting environmentally unsuitable sites from the absences reflecting dispersal limitations (i.e. sites might be environmentally suitable but the species has not reach those places yet) and use only the former (not the latter) set of absences to safely model the potential distribution and spread of a non-native invasive species.

The DIARS project has also demonstrated that LiDAR-derived variables capturing the complex 3D structure of vegetation like in forest ecosystems can be combined together with hyperspectral bands to model leaf nutrient content (nitrogen, phosphor, carbon) in the tree canopy at very fine spatial resolution. Interestingly, field data on leaf nutrient content of several native tree species as well as *Prunus serotina* (Fig. 1), a non-native and invasive tree species in European forests, suggests that *Prunus serotina* is changing nitrogen, phosphorus and carbon cycles to its own advantage. By incorporating this important finding from field observations into the above-mentioned model that combines LiDAR data with hyperspectral data, the DIARS project has further illustrated the potential of remote sensing technologies to map the impact of a non-invasive plant on biogeochemical cycles.

Finally, the DIARS project has produced a free and open-access toolbox (cf. the DIARS toolbox) with: (i) open-source codes to be used in the free and open source software (FOSS) R and GRASS GIS; (ii) a new R package (cf. iSDM: https://cran.r-project.org/web/packages/iSDM/); (iii) guidelines; and (iv) hands-on training based on real data collected throughout the DIARS project. The DIARS toolbox and its iSDM companion ensure a proper knowledge transfer that aims at engaging and educating stakeholders and end users.

3. Objectives of the research

The objectives of this three-year project are twofold. The first objective is to demonstrate and to characterize the ecosystem impact of non-native invasive plant species through the combined use of field data and remotely sensed data. The second aim is to support monitoring, prediction of spread and risk assessment of non-native invasive plant species through remote sensing as preconditions for taking management measures for mitigation. The more specific research objectives of DIARS are to:

1. Quantify, study and better understand the effects of biological invasion on ecosystem properties, through methods of remote sensing (O1):

2. Develop and validate an approach to create accurate fine scale baseline maps and predictive models of the distribution of invasive plant species at the landscape scale (O2);

3. Assess possibilities and constraints for generalization of the proposed advanced remote sensing approaches across ecosystems and invasive species (O3);

4. Develop and disseminate a toolbox for the detection, mapping and prediction of the distribution of invasive plant species at the landscape scale, and to assess their impact on ecosystem properties (O4);

5. Provide knowledge transfer and a hands-on training for ecologists, conservation biologists, policy makers and landscape managers across Europe (O5).

4. Project activities and achievements

4.1. General description of activities over the duration of the project

Before addressing the five above listed objectives (O1-O5), the first 20 months, starting from January 1st 2014, of the DIARS project duration (three years) were spent on data gathering (both field and remote sensing data) and data processing. We can say that the data collection campaigns (and subsequent processing) were very successful consequently enabling us to perform the tasks and analyses as written in the project proposal (see the table of deliverables). The only major readjustment from the initial project proposal is that we were not able to find a suitable study site in Southern

France for *Oxalis pes-caprea*, which was one of the three non-native plant species initially listed in the project proposal. Hence, in addition to the Sylt (DE) and Compiègne (FR) study sites where *Campylopus introflexus* and *Prunus serotina* occur, respectively, we decided to select a 2nd study site (Averbode Bos & Heide, BE) (Fig. 3) where *Campylopus introflexus* also occurs, while also including *Rosa rugosa* (Fig. 1), a third non-native invasive species which occurs on the island of Sylt.
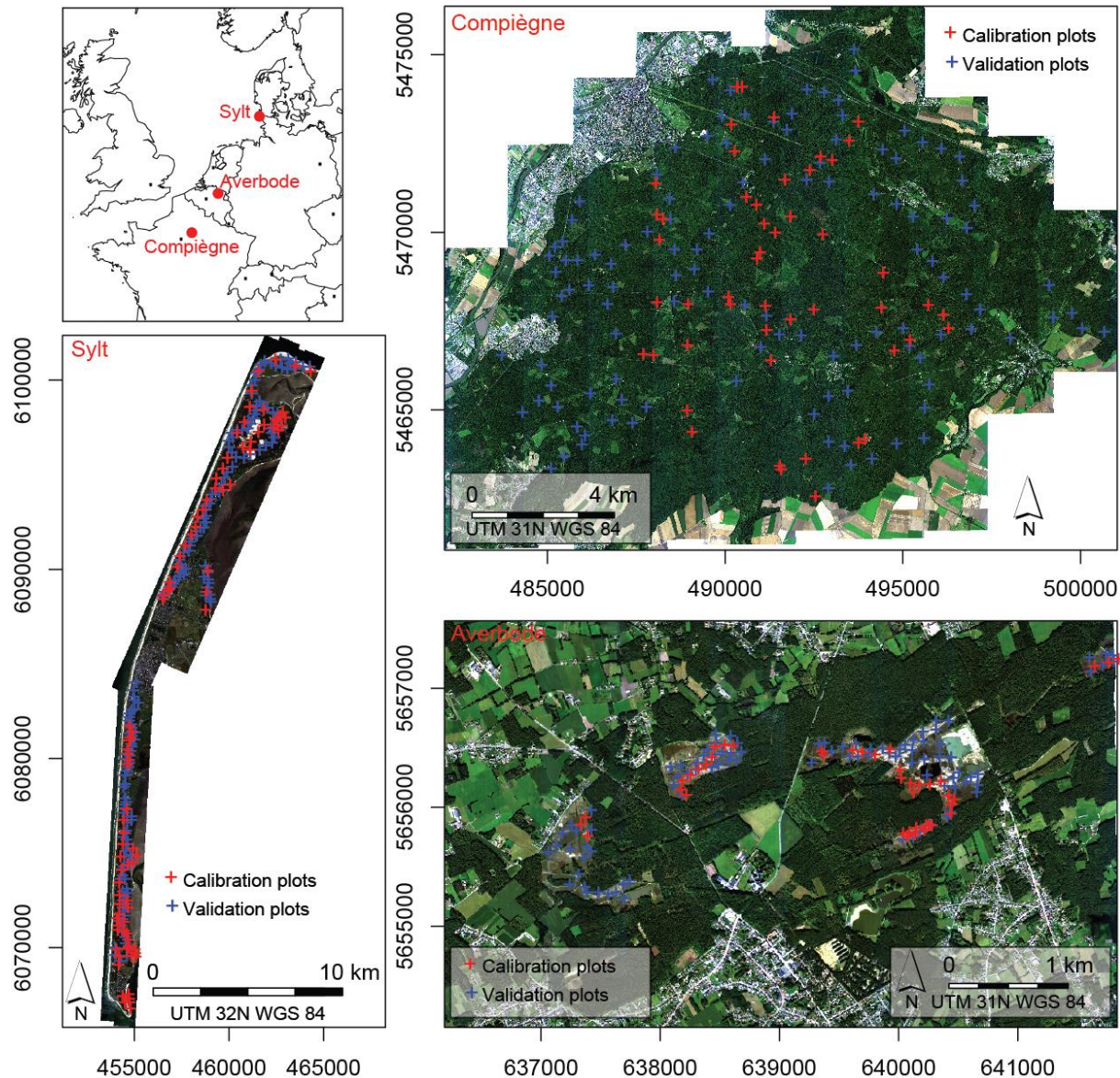

Figure 3: True colour composite images obtained from the Airborne Prism EXperiment hyperspectral spectrometer (APEX) operated by VITO across the three study sites.

- Field data were collected by almost all partners (VITO, KUL, FAU, KIT and UPJV) involved in the DIARS project. Two main field campaign were carried out in the summers 2014 (calibration and validation data collected for all three study sites as well as canopy reflectance spectra collected for *Campylopus introflexus* and *Rosa Rugosa*: VITO, KUL, KIT and FAU) and 2015 (additional calibration and validation data as well as leaf canopy samples collected in Compiègne: KUL, KIT and UPJV). In the proposal it was promised to collect canopy reflectance spectra at the beginning, middle and end of the growing season using a field spectroradiometer covering the 350-2500 nm spectral domain with a 1 nm spectral resolution and this for all study species. From a practical point of view, however, it was not feasible to collect spectra over the whole growing season and for *Prunus serotina*. We did however collect spectra for several plant species (most abundant plant species, including *Rosa rugosa* and *Campylopus introflexus*) on the Island of Sylt as well as in the

study site of Averbode and two other study sites in Belgium (not part of DIARS: Kalmthoutse Heide and Landschap de Liereman) in order to test consistency/transferability between study sites (O3). All the necessary field data were collected before October 2015.

- All hyperspectral remote sensing data were successfully acquired by VITO over all three study sites using the Airborne Prism EXperiment hyperspectral spectrometer (APEX). All APEX flights were operated by VITO and the resulting data was processed using VITO's in-house processing centre. The resulting geometrically, radiometrically and atmospherically corrected images (Fig. 3) were delivered to the DIARS network in February 2015.

- LiDAR data were successfully acquired by UPJV for two of the three study sites (Sylt and Compiègne). For Sylt, LiDAR data acquisition was managed by UPJV and subcontracted by [AERODATA France](). For Compiègne, LiDAR images were not acquired on the DIARS budget but via another project (SYLVANTIC) managed by the "[Office National des Forêts]()" (ONF), one of the stakeholders involved in the DIARS project and with which UPJV interacts on a regular basis. Therefore, LiDAR images over the Compiègne forest, also acquired by AERODATA France, belongs to the ONF but were subsequently made available within the DIARS project (cf. Attachment 1 in the signed Consortium Agreement: Background Included). From the total amount of money that was initially planned as subcontracting for aircraft measurements with LiDAR sensor (60000 EUR, UPJV), 33000 EUR has been spent to cover the entire island of Sylt (cf. a study area much larger than initially planned in the project proposal since LiDAR data for Compiègne were available for free). The total point density largely exceeds 10 points/m² for both study sites. The raw point cloud data were processed by AERODATA France for both study sites to classify points as ground, vegetation, building or water and to generate digital elevation models (DEMs) as well digital terrain models (DTMs) at very fine spatial resolution (50 cm). All grid layers (DEMs and DTMs) as well as the raw point clouds for Sylt and Compiègne were delivered to the DIARS network in November 2014, during the first DIARS meeting. LiDAR data from Averbode are also freely available since mid-2016 (provided by the Flanders Geographical Information Agency) and therefore no other LiDAR flight campaign has been planned within DIARS. Note that the 27000 EUR left from the initial budget dedicated to LiDAR data acquisition (ANR budget, UPJV) was used to cover expenses for leaf chemical analyses (cf. WP5).

From the middle of the second to the third year of the project (2015-2016), we launched several analyses to address the first three objectives (O1-O3). This included:

- Comparing the spectral characteristics and spectral separability index between native (*Ammophila arenaria*, *Calluna vulgaris*, *Corynephorus canescens*, *Empetrum nigrum*, *Erica tetralix*, *Hypnum cupressiforme*, *Salix repens*, and *Vaccinium uliginosum*) and non-native (*Campylopus introflexus* and *Rosa rugosa*) plant species for the Sylt study site and the Belgian study sites (Averbode and 2 other study sites) (VITO: O2 and O3). These analyses were conducted before October 2015 and were used in the model transferability publication

- Generating several fine-grained environmental grids for the Compiègne and Sylt study sites based on both field data and LiDAR data (UPJV: O2 and O3). Initially, it was plan to hire a one-year postdoc (ANR budget, UPJV) to produce LiDAR-derived metrics characterizing the 3D structure of the vegetation and landscape features. However, the leader of this task (**Djemâa Kachi**) from the "Modélisation, Information & Systèmes" (MIS) (https://mis.u-picardie.fr/) lab at UPJV had to retract from the project because of illness after the first year of the project, in January 2015. We have worked a way out by transferring this task to **Tarek Hattab** who was employed as a two-year (2015-2016) postdoc at UPJV under the supervision of **Jonathan Lenoir** (UPJV: WP4). Despite a delay due to the above-mentioned issue, this task was completed in December 2015. Note that the money that was initially planned for subcontracting a one-year postdoc to perform this task during 2015 (cf. WP3) (ANR budget, UPJV) was instead used during the last year of the project (2016) to employ

Carol Ximena Garzón-López as a one-year postdoc, under the supervision of **Jonathan Lenoir** (UPJV) and **Duccio Rocchini** (FEM: WP6), working on developing and disseminating a toolbox for the end user (FEM and UPJV: O4).

- Mapping the actual distribution of *Campylopus introflexus* and *Rosa rugosa* across the island of Sylt at very high spatial resolution through the combined use of field data and hyperspectral images (FAU: O2 and O3). The maps for both species were delivered before October 2015.

- Modelling the realized and potential distributions of *Prunus serotina* across the forest of Compiègne at very high spatial resolution through the combined use of field data and LiDAR images (UPJV: O2 and O3). Both the realized and potential distributions of *Prunus serotina* were delivered in December 2016. Due to time constraints and the tasks' redistribution caused by the retraction of **Djemâa Kachi**, this set of analyses could only be conducted for Compiègne. However, by providing codes as well as an online tutorial, through the DIARS toolbox (cf. O4 and O5), it is possible to run these analyses also for *Campylopus introflexus* and *Rosa rugosa* across the island of Sylt.

- Simulating the future spread of *Prunus serotina* across the forest of Compiègne at very high spatial resolution through the combined use of niche-based habitat suitability models and mechanistic models that account for population dynamics and different forest management scenarios (UPJV: O2 and O3). Analyses are done since December 2016 with few adjustments carried out between January and May 2017. These simulations of future spread will not be conducted *Campylopus introflexus* and *Rosa rugosa* due to the heavy and time-consuming computations involved in these analyses.

- Modelling the impact of *Prunus serotina* on ecosystem processes (biogeochemical cycles) in the forest of Compiègne through the combined use of field data (leaf chemical contents) and airborne remote sensing data (LiDAR and hyperspectral images) (KIT: O1). Maps of leaf nitrogen and phosphorus contents at very high resolution (25 m) throughout the entire forest of Compiègne were generated in December 2016. Actual costs for sampling and analyzing the chemical content of the leaves exceeded the anticipated costs so that we only covered the Compiègne and Sylt study sites..

During the last year of the project (2016), **Carol Ximena Garzón-López** worked on a website construction to host a tutorial with guidelines, hands-on-training as well as open-source codes in R and GRASS GIS to ensure the delivery of the DIARS toolbox for the end user (O5 and O6). The DIARS toolbox is available at http://diarsproject.github.io/DIARS/HomeDIARS.html and a manuscript describing the DIARS toolbox has been published so that it can be properly cited.

To 'steer' the DIARS project, a steering committee consisting of 2 scientific experts and 3 stakeholders (see section 5 on the stakeholder engagement during project's life for a detailed composition of the steering committee) was set up after the first DIARS meeting held in Leuven (BE) in November 2014. The first steering committee meeting was held in Leuven (BE) in October 2015 while the second and final steering committee meeting was held in Karlsruhe (DE) in December 2016.

4.2. Table of deliverables

Deliverable (D) and Milestone (M)			Lead partner (country)	Date delivered	Comments
WP	D/M	*Full name*			
	D.00	*Consortium agreement*	*UPJV (FR)*	04/11/2014	***Completed**. Jonathan Lenoir (UPJV) wrote and circulated the main document, which was signed by all partners in November 2014.*
WP1	D.01	*Location of the 5*5 km study sites within the three selected study areas*	*KUL (BE)*	March 2014	***Readjusted**. 2 (Sylt, DE; Compiègne, FR) of the 3 study sites are much larger (70 km^2 and 144 km^2, respectively) than initially planned (25 km^2) (see Fig. 1).*

Deliverable (D) and Milestone (M)			Lead partner (country)	Date delivered	Comments
WP2	D.02	*Set of hyperspectral signatures and spectral libraries for invasive species and co-occuring native vegetation in the different study sites (baseline data for further remote sensing analysis)*	*VITO (BE)*	December 2016	*__Readjusted__. Canopy reflectances were gathered for both native and non-native species but only the Sylt (DE) and Averbode (BE) study sites because it was not feasible to collect canopy reflectance spectra for tree species in Compiègne (FR). As a compensation, 2 extra study sites in Belgium were sampled to collect canopy reflectance spectra of native and non-native species.*
WP3	D.03	*Report with the detailed analysis of the spectral characteristics of invasive and native plants in the study sites*	*VITO (BE)*	December 2016	*__Completed__. 2 master theses (Sylt, DE; Averbode, BE) were done in the framework of this deliverable while the results were also incorporated in the model transferability paper.*
WP2	D.04	*Set of ground reference data (vegetation analysis) for the calibration of one-class classifiers*	*KUL (BE)*	August 2014	*__Completed__. All calibration vegetation plots were sampled during summer 2014.*
WP3	D.05	*Set of ground reference data (vegetation analysis) for the validation of the created maps*	*FAU (DE)*	August 2015	*__Completed__. Calibration and validation data were simultaneously gathered during summer 2014 but additional validation data for Compiègne (FR) and Averbode (BE) were acquired in July 2015.*
WP2	D.06	*Detailed description and chemical analysis of vegetation and soil at all three study sites*	*KUL (BE)*	December 2015	*__Readjusted__. Leaf chemical analyses as well as soil chemical analyses were carried out for 2 study sites (Sylt, DE; Compiègne, FR) only. Actual costs for sampling and analyzing the chemical content of the leaves exceeded the anticipated costs.*
WP2	D.07	*Set of geometrically and radiometrically calibrated aircraft images (hyperspectral and LiDAR) over the study sites*	*VITO (BE)*	June 2015	*__Completed__. Processed hyperspectral data (strips) were delivered for all 3 study sites in February 2015 and mosaics were generated in June 2015. Processed LiDAR data (digital elevation and terrain models) for Sylt (DE) were delivered in November 2014. For Compiègne (FR), all processed LiDAR data were directly available from the Office National des Forêts (ONF). LiDAR data from Averbode (BE) are also freely available (provided by the Flanders Geographical Information Agency) since mid-2016.*
WP3	D.08	*Set of raw LiDAR metrics for characterizing 3D structure of canopies and landscape in the three study sites*	*UPJV (FR)*	December 2015	*__Completed__. The leader of this task (Djemâa Kachi) from the "Modélisation, Information & Systèmes" (MIS) (https://mis.u-picardie.fr/) lab at UPJV had to retract from the project because of illness after the first year of the project, in January 2015. Jonathan Lenoir (UPJV) took over the responsibility of this task.*
WP4	D.09	*Fine-grained environmental grids across each of the three study sites*	*UPJV (FR)*	December 2015	*__Completed__. Note that fine-grained environmental grids could be delivered for only 2 (Compiègne, FR; Sylt, DE) of the 3 study sites. LiDAR data from Averbode (BE) are now available (since mid-2016) but due to time constraints, the fine-grained environmental grids for that 3rd study site could not be delivered during the project duration and therefore will not be used.*
WP5	D.10	*Interpreted grids representing the distribution of plant functional types*	*KIT (DE)*	Mid 2017	*__Readjusted__. In the forest of Compiègne (FR), canopy species are too similar, concerning plant functional types and thus not suited for a remote sensing approach. Due to time constraints, maps were only be calculated for Sylt (DE).*
WP3	D.11	*Detailed documented flowchart to create accurate fine scale baseline maps of the distribution of invasive plant species*	*FAU (DE)*	Mid 2016	*__Completed__. This deliverable is covered in the first publication, which came out of the project written by Sandra Skowronek (PhD student within DIARS).*
WP3	D.12	*Set of fine scale baseline maps of current distribution of invasive plant species over the study sites*	*FAU (DE)*	June 2016	*__Readjusted__ This was done for the Sylt (C. introflexus and R. rugosa) (DE) and Averbode (C. introflexus) (BE) study sites as well as for the 2 additional Belgian study sites (Kalmthout & Liereman). Compiègne (P. serotina) (FR) was not performed due to time constraints*
WP5	D.13	*Statistics relating organismic indicators of ecosystem functioning to degrees of infestation*	*KIT (DE)*	Mid 2017	*__Readjusted__. Due to the lack of independent distribution data, statistics could not be calculated for C. introflexus and R. rugosa. For P. serotina, no suitable maps could be calculated.*
WP4	D.14	*Set of fine scale baseline maps of the habitat suitability of invasive plant species over the study sites*	*UPJV (FR)*	September 2016	*__Readjusted__. Due to analytical problems and time constraints (cf. D.08 delayed), fine scale baseline maps of the habitat suitability could only be completed for the different life stages (cf. seedling, sapling and tree life stages) of P. serotina across the forest of Compiègne (FR).*

Deliverable (D) and Milestone (M)			Lead partner (country)	Date delivered	Comments
WP5	D.15	Interpreted grids representing the distribution of biochemical and structural traits	KIT (DE)	Mid 2017	**Readjusted** Calculation of maps is completed for Compiègne (FR). For Sylt this is still planned in near-future. Note that biochemical and structural traits were not collected for Averbode (BE).
WP5	D.16	Statistics relating biochemical and structural indicators of ecosystem functioning to degree of infestation	KIT (DE)	May 2017	**Readjusted**. Due to the lack of independent distribution data on C. introflexus and R. rugosa, statistics could only be calculated for P. serotina.
WP5	D.17	Interpreted grids representing carbon sequestration across gradients of infestation	KIT (DE)	March 2017	**Completed**. Maps of wood volume for the forest of Compiègne (FR) and maps of above ground biomass for Sylt (DE) are now available. Note that for the study site in Averbode (BE), field work did not include biomass sampling.
WP7	D.18	Two day training course	KUL (BE)	Mid 2017	**Completed** A workshop & excursion was organized on Sylt for local stakeholders + VITO gave hand-on training course at the EUFAR RS4ForestEBV training course in July using the DIARS outcome.
WP4	D.19	Fine-grained maps of the potential future distribution of the three invasive plants across their study sites (task 4.3)	UPJV (FR)	Mid 2017	**Delayed**. A hybrid model (combining statistical and mechanistic approaches) as well as several scenarios of future forest management are under construction to model the future spread of P. serotina across the forest of Compiègne (FR). A delay was introduced because of analytical issues (cf. heavy computations and a very complicated life cycle to model).
WP4	D.20	List of landscape sites most vulnerable to invasion	UPJV (FR)	September 2016	**Readjusted**. Due to analytical problems and time constraints (cf. D.08 delayed), maps of invasion vulnerability could only be completed for each of the different life stages (cf. seedling, sapling and tree life stages) of P. serotina across the forest of Compiègne (FR).
WP7	D.21	Training course manual	KUL (BE)	Mid 2017	**Completed**. A website hosting the DIARS toolbox and providing guidelines as well as hands-on training has been released as well as a publication presenting the DIARS toolbox.
WP6	D.22	Complete code for spatial algorithms reproducibility	FEM (IT)	Mid 2017	**Completed** A website hosting the DIARS toolbox and providing guidelines as well as hands-on training has been released as well as a publication presenting the DIARS toolbox.
	D.23	Scientific publications in international journals	ALL	Mid 2018	**Comleted**. Several scientific papers have already been published b
	M.01	Kick off meeting with stakeholders consensus on research program	VITO (BE)	November 2014	**Completed**. The first DIARS meeting was postponed because some of the partners encountered a large delay in having access to their respective budget.
WP2	M.02	Acquisition of detailed data on soil and vegetation in 135 study plots across the three study sites	KUL (BE)	August 2015	**Completed**. Note that soil data had been sampled for only 2 (Compiègne, FR; Sylt, DE) of the 3 study sites.
WP2	M.03	Acquisition of a set of geometrically and radiometrically calibrated aircraft images (hyperspectral and LiDAR) over the study sites	VITO (BE)	June 2015	**Completed**. Note that LiDAR data from Averbode (BE) is only available since mid-2016 (provided by the Flanders Geographical Information Agency) and thus will not be used within DIARS.
WP4	M.04	Fine-grained environmental grids across each of the study sites	UPJV (FR)	December 2015	**Completed**. Note that fine-grained environmental grids could be delivered for only 2 (Compiègne, FR; Sylt, DE) of the 3 study sites.
WP3	M.05	Fine-grained baseline maps of current distribution of invasive plant species over the study sites	FAU (DE)	June 2016	**Completed**. Maps are ready for Sylt (R. rugosa & C. introflexus) (DE), Averbode (C. Introflexus) (BE) and 2 additional Belgian study sites.
WP4	M.06	Fine-grained maps of the habitat suitability of the invasive plants	UPJV (FR)	September 2016	**Readjusted**. Due to analytical problems and time constraints (cf. D.08 delayed), fine scale baseline maps of the habitat suitability could only be completed for the different life stages (cf. seedling, sapling and tree life stages) of P. serotina across the forest of Compiègne (FR).
WP5	M.07	Interpreted grids representing the distribution of plant functional types, biochemical and structural traits	KIT (DE)	Mid 2017	**Readjusted**. Due to analytical problems and time constraints, this milestone could only be completed for a subset of the proposed grids and for two of the study sites (cf. D13, D15).

Deliverable (D) and Milestone (M)			Lead partner (country)	Date delivered	Comments
WP5	M.08	Interpreted grids representing carbon sequestration across gradients of infestation	KIT (DE)	March 2017	**Completed**. *Maps of wood volume for the forest of Compiègne (FR) and maps of above ground biomass for Sylt (DE) are now available. Note that for the study site in Averbode (BE), field work did not include biomass sampling.*
WP6	M.09	Development of spatial algorithms	FEM (IT)	December 2016	**Completed**. *The iSDM R package is now available on the CRAN website.*
WP4	M.10	Fine-grained maps of potential future distribution of the invasive species in the study sites	UPJV (FR)	Mid 2017	**Delayed**. *A hybrid model (combining statistical and mechanistic approaches) as well as several scenarios of future forest management are under construction to model the future spread of P. serotina across the forest of Compiègne (FR). A delay was introduced because of analytical issues (cf. heavy computations and a very complicated life cycle to model).*
WP6	M.11	Software testing & publication	FEM (IT)	Mid 2017	**Completed** *A website hosting the DIARS toolbox and providing guidelines as well as hands-on training has been released as well as a publication presenting the DIARS toolbox.*
WP7	M.12	Organizing of a two-day workshop	KUL (BE)	Mid 2017	**Completed** *A workshop & excursion was organized on Sylt for local stakeholders + VITO gave hand-on training course at the EUFAR RS4ForestEBV training course in July using the DIARS outcome.*
	M.13	Organizing of a final symposium	VITO (BE)	December 2016	**Completed**. *See section 5 on stakeholder engagement during project's life.*
	M.14	Results published	ALL	Mid 2018	**Completed**. *Several scientific papers have already been published but one is still ongoing and will soon be submitted.*

4.3. Scientific outcomes

Quantifying, studying and better understanding the effects of biological invasion on ecosystem properties, through methods of remote sensing (O1)

To study the effects of *Prunus serotina* on vegetation traits and ecosystem properties through remote sensing, we had to focus on methodological issues first. Specifically, the mapping of leaf chemical contents using hyperspectral remote sensing appeared to be challenging, because of its strong covariation with structural canopy properties, which are also influencing the reflectance spectra. Hitherto, applications of hyperspectral remote sensing to map leaf chemical contents have mainly focused on crops or vegetation with homogeneous canopies, in order to minimize the influence of varying canopy structure. Because *Prunus serotina*, a forest gap species, is bound to structurally heterogeneous forests, the analyses of its impacts on leaf chemical contents required to develop a new approach for mapping leaf nitrogen (N) and phospherous (P) contents. In this new approach, we integrated predictor variables derived from LiDAR data capturing the biophysical complexity of the canopy into predictive models of leaf N and P contents based on hyperspectral data. We used partial least squares regression models integrating community weighted means of leaf N and P contents from 50 field plots, as well as 245 hyperspectral bands and 18 LiDAR-derived variables as predictors. LiDAR-derived variables improved the model's explained variances for N mass (R^2_{val} = 0.31 vs. 0.41; $RSME_{val}$ = 3.3 vs. 3.0) and P mass (R^2_{val} = 0.45 vs. 0.63; $RSME_{val}$ = 15.3 vs. 12.5). The most important spectral bands were located in the visible part of the spectrum for N mass and throughout the whole spectral range for P mass. Our results indicate that remote sensing is a powerful tool for mapping canopy biochemistry also in structurally heterogeneous forests (Fig. 4). These outcomes help to understand co-variation of canopy structure and leaf chemistry. A paper presenting these findings in more details has been published in the international research journal *Remote Sensing of Environment*.
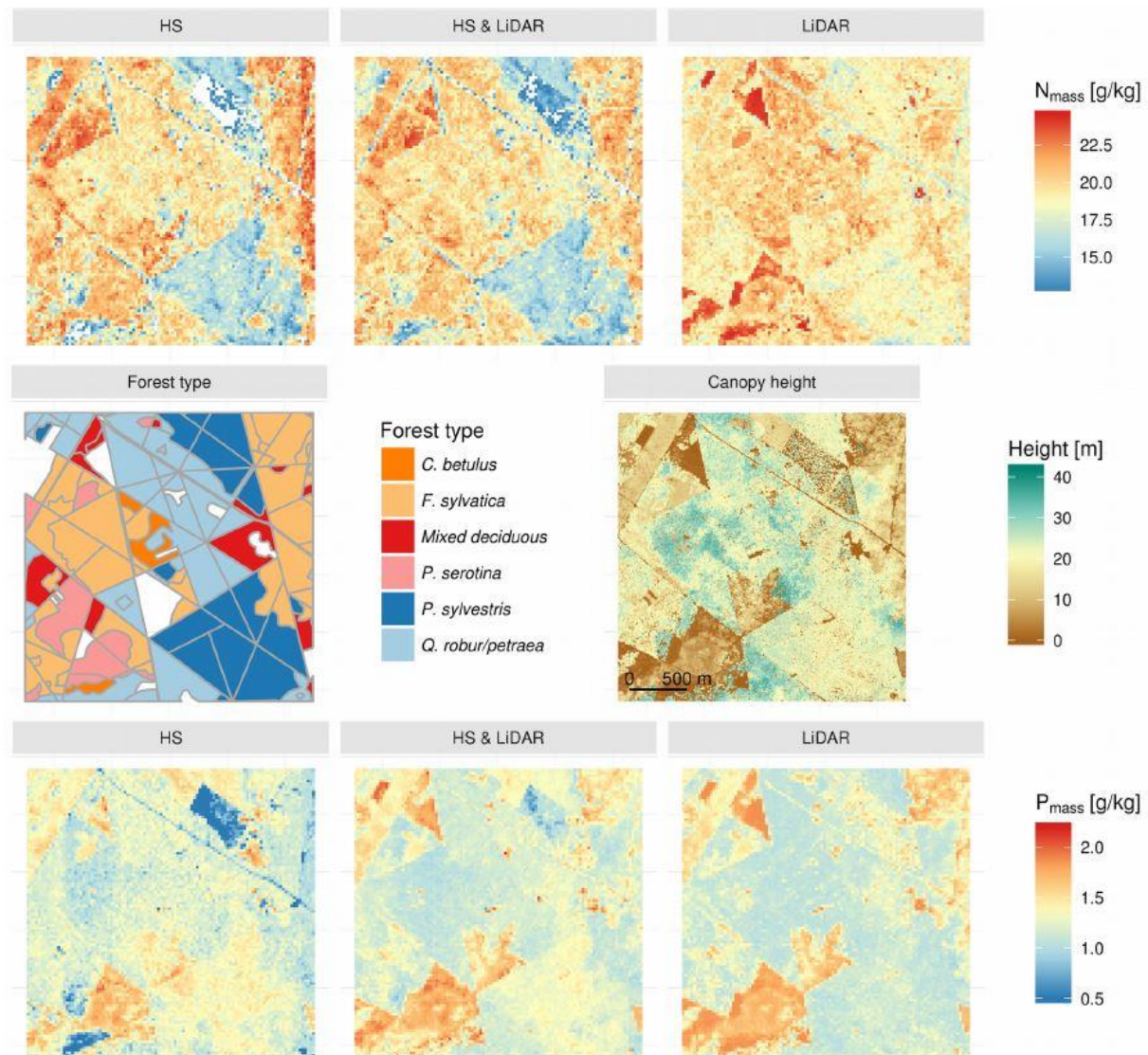
Figure 4: Map sections from the forest of Compiègne (FR) showing forest types represented by their dominant tree species, a canopyheight model (both in the center) and median predictions of canopy level N mass (above) and P mass (from models trained by hyperspectral bands (HS), LiDAR-derived predictors (LiDAR) or a combination of both (HS+LiDAR).

Resulting maps of canopy leaf N and P contents (Fig. 4) were used together with remotely sensed maps of leaf N:P ratio, wood volume and leaf area index (LAI) to assess the impact of *Prunus serotina* on these vegetation traits. This has lead to publication in the journal Biological Invasions. Indeed, field observations suggest that *Prunus serotina* is changing nitrogen, phosphorus and carbon cycles to its own advantage. A paper presenting these field observations in more details has been recently published in open-access in the international research journal *Frontiers in Plant Science*. Thereby, we focused on fine scale impacts using sampling units covering 25 m × 25 m (hereafter referred to as plot level) and broad scale impacts using forest stands as sampling units. Using linear mixed effect models (LMMs), we linked remotely sensed vegetation traits with *Prunus serotina* invasion, at the plot level and the forest stand level, respectively. Observed effects of *Prunus serotina* were strongly related to the observed forest stand type (beech, oak, pine or mixed deciduous forest). In general, *Prunus serotina* presence was related to lower wood volume reflecting its character as a canopy gap species. Furthermore, *Prunus serotina* presence was related to decreased canopy N:P ratios at both, plot and forest stand level, indicating its potential to alter the chemical composition of forest canopies across broad spatial scales. At the plot level, we also observed lower canopy leaf N content when *Prunus serotina* was present. However, we could not trace up this observation to the stand level. Overall, we could successfully demonstrate the usefulness of remote sensing for studying

plant invasion impacts. Outcomes of experimental or observational field studies used for evaluation of invasion effects have mainly been based on sampling units with limited spatial extent. Our results suggest that such fine scale observations at the plot level provide accurate information on the potential impact of invasive species but lack information about the spatial relevance of such impacts. This gap can be successfully filled by using remote sensing data.

Developing and validating an approach to create accurate fine-scale baseline maps and predictive models of the distribution of invasive plant species at the landscape scale (O2) and assessing possibilities and constraints for generalization of the proposed advanced remote sensing approaches across ecosystems and invasive species (O3)

Focusing on the island of Sylt, we first applied a popularized modelling algorithm (cf. Maxent) to map the actual distribution of *Campylopus introflexus* from hyperspectral remote sensing data only. We used 57 calibration plots, each covering 3 m x 3 m and within which *Campylopus introflexus* occurred (cf. the response variable), and 146 spectral bands remaining after elimination of the bands disturbed by water vapour signal as predictor variables to calibrate a Maxent model of the probability for *Campylopus introflexus* to occur at a given location. Although *Campylopus introflexus* is a small and inconspicuous species, we were able to map its actual distribution (cf. O2) with an overall accuracy of 75 %. The model predicted that *Campylopus introflexus* has already invaded 27% of the island of Sylt (Fig. 5). According to model predictions, the North of the island seems slightly more invaded (31%) than the South (26%) and the centre (22%). Among the different dune habitats, dune grasslands were the most invaded (59%). We therefore concluded that the map we produced from remote sensing is a good alternative to a traditional field mapping approach. One main reason to use such an alternative is the difficulty to detect and accurately estimate occurrences of such a small and inconspicuous species from a long distance and across such a large spatial extent (70 km^2). Even standing directly on a plot, an observer has to search carefully before all occurrences are detected or its presence can be safely excluded. With this important finding, the DIARS project illustrates the potential of hyperspectral images to face the challenge of detecting small-stature invasive plant species like small and inconspicuous moss species. Our findings suggest that hyperspectral remote sensing data have the potential to provide reliable information about the degree of bryophyte invasion, and thus provide an alternative to traditional field mapping approaches over large areas.

Reducing the sampling effort from 57 to 7 calibration plots to challenge the model for early detection of non-native invasive species (cf. O3), our models performed fairly well until sampling effort dropped below 12 plots. This suggests that this first approach can significantly reduce the fieldwork effort to map the actual distribution of a non-invasive native plant, at least for the calibration plots, and that we can also use this approach for species that are not (yet) very widespread. For validation, however, we found that a larger dataset would allow more detailed conclusions on the model performance. Depending on the size of the area and the previous knowledge of the target species, such data (presence for calibration, presence and absence for validation) can be collected within one to 4 weeks by one person, as our experience from this and other field campaigns has proven. A paper presenting these findings in more details has already been published in the international research journal *Biological Invasions*.
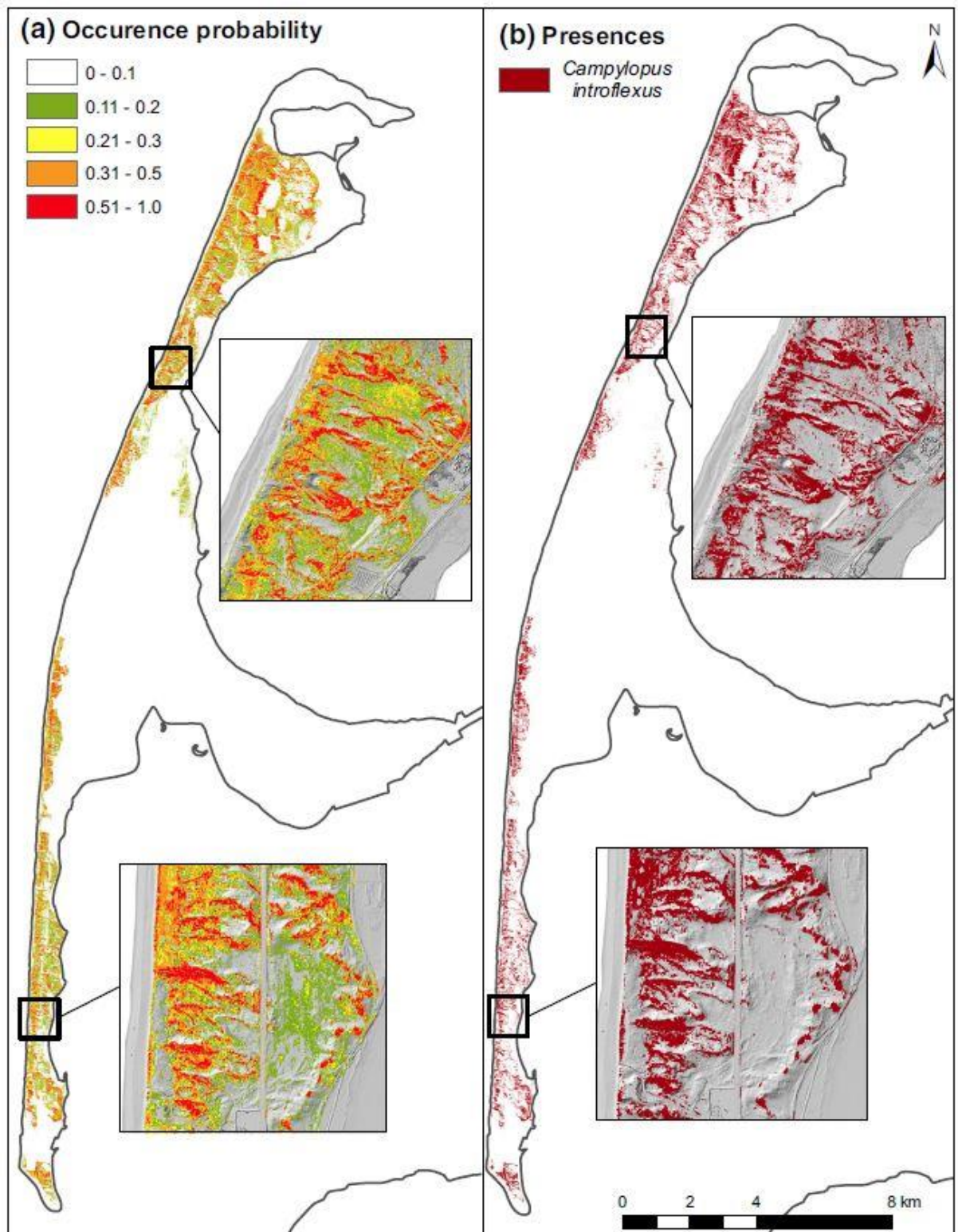
Figure 5: Maps of the predicted probability of occurrence (a) and presence (b) for the invasive bryophyte *Campylopus introflexus* across the island of Sylt (DE). The background in the detailed maps is a LiDAR-derived relief hillshade.

Building on these findings and as an attempt to generalize our methodology (cf. O3), we also evaluated the transferability of Maxent models for detecting *Campylopus introflexus* (Fig. 6). We assessed the feasibility of spatially transferring locally calibrated models for species detection between four different heathland areas in Germany and Belgium and tested the potential of combining calibration data from different sites in one species distribution model. Although our results showed

that the success of transferring models calibrated in one site to another site highly depended on the respective study site; the combined models provided higher test AUC values than the locally calibrated models for three out of four study sites. Furthermore, we also demonstrated the importance of optimizing the Maxent modelling parameters. Overall, our results indicate the potential of a combined model to map *Campylopus introflexus* over most other study areas without the need for new calibration data. A paper presenting these results has been published in the International Journal of Applied Earth Observation and Geoinformation
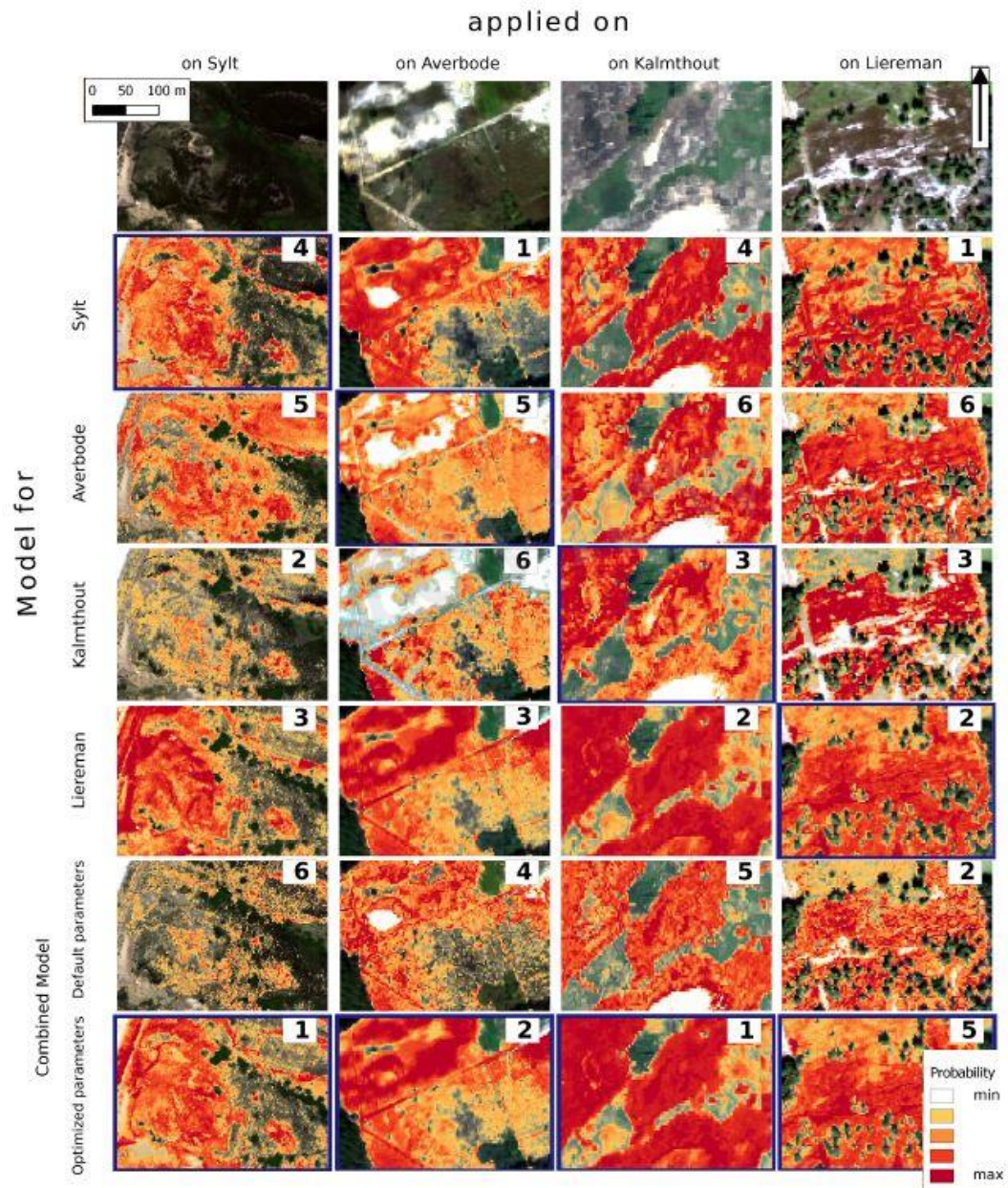

Figure 6: Transferability of Maxent models for detecting *Campylopus introflexus* between four different heathland areas in Germany (Sylt) and Belgium (Averbode, Kalmthout, Liereman). The number in the right corner of each subset map indicates the rank according to test AUC values, 1 being the highest and 6 the lowest rank. Blue boxes highlight the original model and the optimized combined model for each study area, respectively.

Not only it is important to provide tools to remotely map the actual distribution of a non-native invasive and inconspicuous species, but also it is important to model its potential spread across the ecosystem (cf. O2). Unfortunately, the non-equilibrium distribution of invasive species with the environment within the invaded range affects the environmental representativeness (cf. the ecological

space) of species presence-absence data collected from the field (cf. the geographical space) and introduces uncertainty in the observed absences as these may either reflect unsuitable sites or be incidental (cf. O3) (see Fig. 7). Because of that, a blind use of absence data in species distribution models (SDMs), which is the state-of-the-art to project the potential spread of an invasive species, is highly problematic and could potentially lead to erroneous predictions.
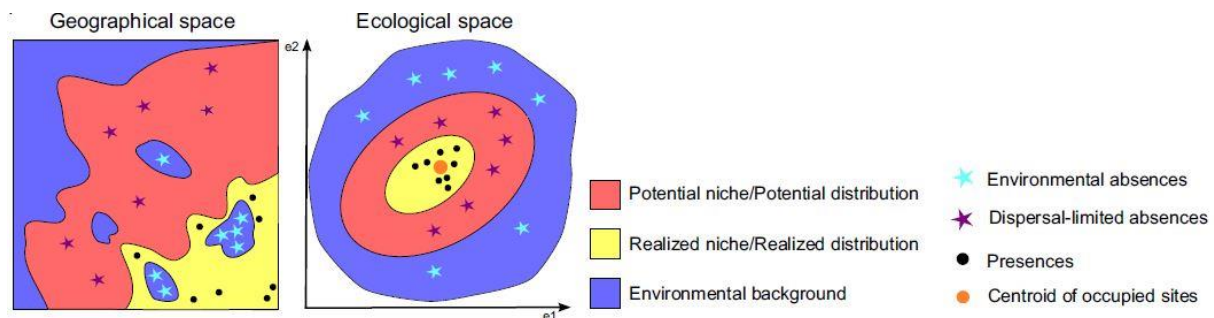

Figure 7: Theoretical representation of the disequilibrium in species' distribution within the invaded range: a well-known challenge when modelling the distribution of non-native invasive species.

To address this challenge, we developed a novel modelling framework to carefully separate the absences reflecting environmentally unsuitable sites from the absences reflecting dispersal limitations (i.e. sites might be environmentally suitable but the species has not reach those places yet). Once absences observed in the field are carefully sorted into environmental vs. dispersal-limited absences, it is then possible to model both the realized (where it currently occurs) and potential (where it could spread) distributions of invasive species. The novelty of our framework lies on the simple fact that if one aims at modelling the potential distribution, then only environmental absences (and not dispersal-absences) should be used and considered when calibrating the model. For the realized distribution, however, all absences (environmental and dispersal-limited absences) should be used when calibrating the model. Although this makes perfect sense, we are the first to provide a framework that allows for such a careful distinction in the absence data collected from the field. To evaluate the performance of our framework, we first conducted a comprehensive test based on a virtual species for which we know exactly the realised and potential distributions and thus whether or not an absence is due to environmental or dispersal limitations, because we simulated it. Our results based on this virtual species show that for the potential distribution, model performances were always higher when using only the set of environmental absences for model calibration compared with a baseline situation that uses all absences (cf. state-of-the-art). To illustrate and challenge this new and unique framework, we decided to apply it on *Prunus serotina* across the forest of Compiègne. The choice of *Prunus serotina* is important as this tree species, with a very complicated but well-known life cycle, invades the forest of Compiègne in all vegetation layers (herbaceous, shrub and tree layers) in a nested manner (seedlings have invaded a larger extent of the forest than shrubs and so on for shrubs compared with trees that need more time to reach the canopy layer). When applying our framework to the real case of *Prunus serotina*, we found that 80%, 68% and 46% of absences (cf. real absences from field observations) have a high probability to be dispersal-limited absences for the tree, shrub and seedling life stages, respectively. By removing these likely dispersal-limited absences from the calibration and validation datasets, the models' predictive performances increased for all life stages. We found a higher improvement for the tree life stage, with the True Skill Statistic (TSS) values increasing from 0.11 to 0.71, than for the shrub and seedling life stages, with TSS values increasing from 0.36 to 0.78 and from 0.25 to 0.68, respectively. Using a standard RGB (red, green, blue) colour space to plot spatial predictions of the potential versus the realized distributions for each life stage separately, we found that the projected potential distribution of the three life stages was substantially similar, while the mapped realized distribution showed nested patterns of distribution with the realized distribution of trees being nested within the one of shrubs and seedlings (Fig. 8). Our framework helps overcoming the conceptual and methodological limitations (cf. O3) of the disequilibrium in species' distribution models inherent to invasive species and enables managers to robustly estimate both the realized and potential distributions of invasive species (cf. O2). A paper presenting these findings in more details has already been published in the international research journal *Diversity and Distribution*.

Additionally, the "iSDM" R package has been developed by the DIARS consortium and is freely available online, together with a tutorial, to help the user mapping the realized distribution and modelling the potential distribution of non-native invasive species.
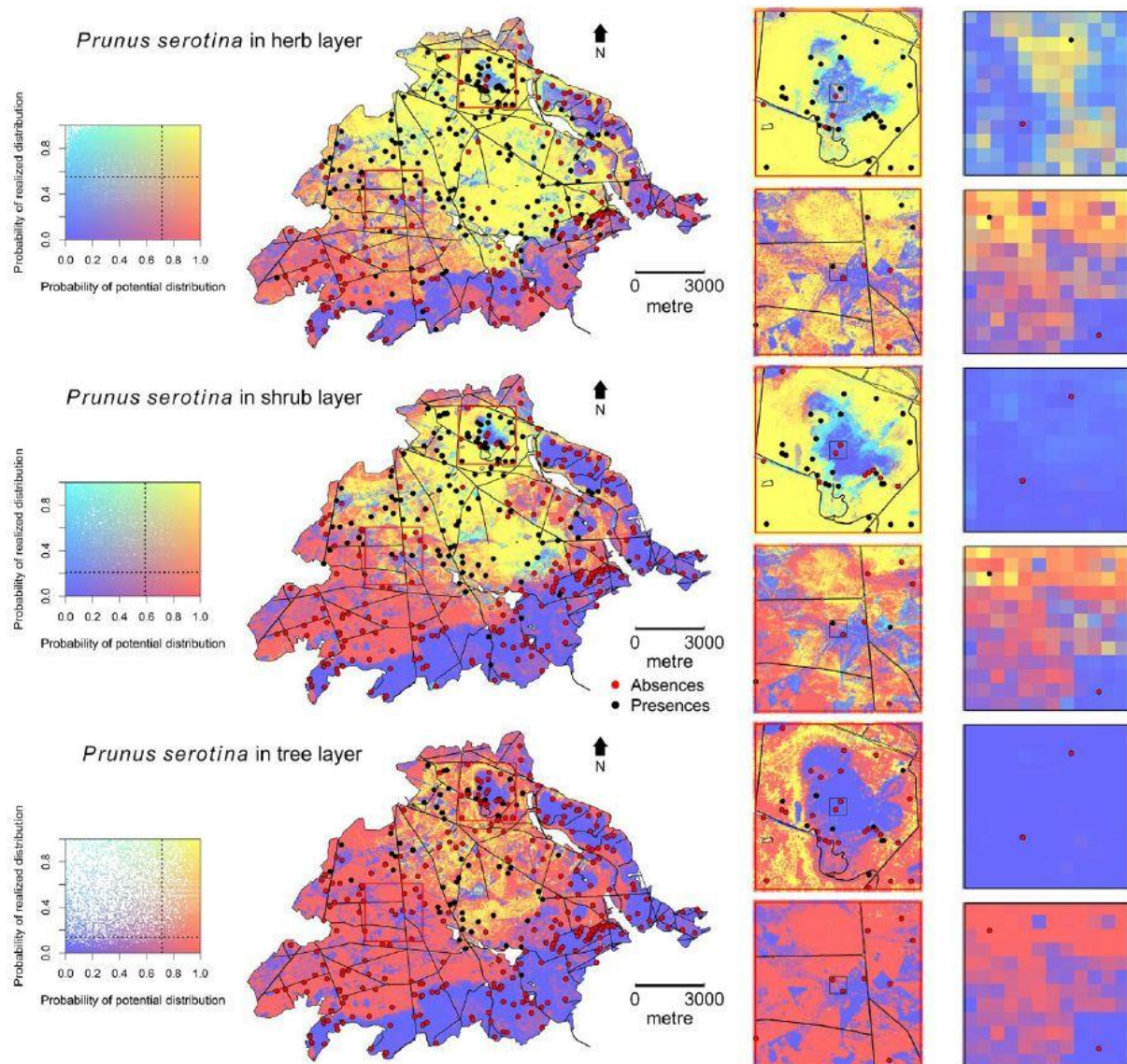

Figure 8: Maps of the potential versus the realized distributions for each *Prunus serotina* life stage across the forest of Compiègne (FR). Yellowish colours in the three-dimensional RGB (red, green, blue) colour space represent areas with a high likelihood to be already invaded. Reddish colours represent areas not yet invaded but with a high risk of invasion. Dark blue colours represent areas with a low risk of invasion. Light blue colours represent areas likely to be invaded but which should not be given environmental conditions (cf. discrepancies between the realized and the potential distributions suggesting source–sink dynamics).

Regarding the future spread of *Prunus serotina* across the forest of Compiègne, we recently finalised a spatially-explicit hybrid model that not only take into account the complex life cycle of *Prunus serotina* but also the impact of forest management (Fig. 9). This hybrid model combines both correlation-based approaches to project the habitat suitability of *Prunus serotina* across the forest of Compiègne for each life stage separately and at each time step with process-based approaches to mechanistically model the population dynamics of *Prunus serotina*. Several scenarios of future management strategies across the forest of Compiègne have been simulated to assess the potential impacts of forest management on the spread of *Prunus serotina* across the forest of Compiègne. Preliminary results suggest that converting actual forest stands to *Fagus sylvatica* as the chief target tree species for wood production will slow down, halt and potentially mitigate the spread of *Prunus*

serotina while a conversion to *Pinus sylvestris* will amplify the spread of *Prunus serotina* dramatically. We are currently writing a scientific paper to be submitted in *Remote Sensing in Ecology and Conservation*.
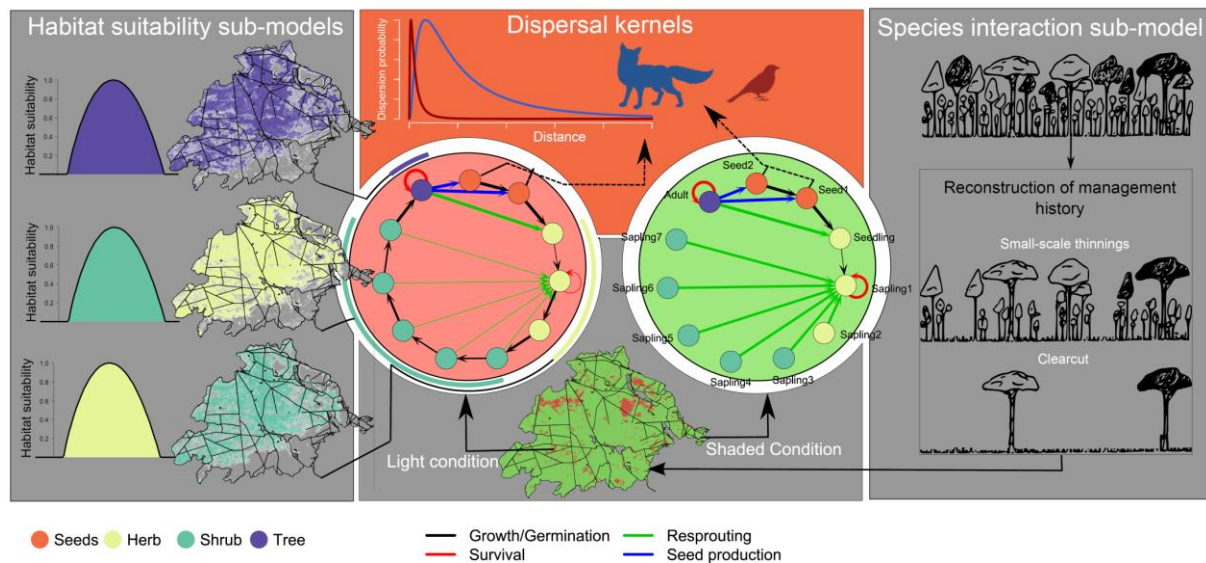

Figure 9: A schematic representation of the hydrid model develop within DIARS to predict the future spread of *Prunus serotina* across the forest of Compiègne (FR). This complex model combines habitat suitability sub-models (cf. Fig. 8) together with knowledge on the population dynamic of *Prunus serotina* through establishment, growth, maturation, seed production and seed dispersal (cf. seeds are mainly dispersed by birds and foxes) as well as with a species interaction sub-model that account for the impacts of canopy density on light conditions on the ground and the subsequent feedback on the population dynamic of *Prunus serotina*.

Developing and disseminating a toolbox for the detection, mapping and prediction of the distribution of invasive plant species at the landscape scale (O4)

Within the framework of DIARS, we developed a toolbox that provide an easy-to-use, flexible, transparent and open-source set of tools to sample, map, model and assess the impact of plant invasions using two high-resolution remote sensing products (hyperspectral and LiDAR images). The DIARS toolbox consists of a series of tutorials that include exemplary datasets of field observations, LiDAR-derived spatial grids and hyperspectral images as well as several R functions to optimize sampling design in the field, model invasive species distribution and to assess the impact of invasive plants on some ecosystem functions. The tutorials are organized into two main sections: data preparation and applications (Fig. 10). The first section contains three tutorials on hyperspectral data processing, LiDAR data processing and the implementation of the method and R functions to generate a systemic sampling and to prepare data collection in the field (Fig. 10). The second section presents the three main applications of the toolbox: mapping, modeling and impact assessment (Fig. 10). More information on the DIARS toolbox can be found in the following publication. Furthermore, the DIARS toolbox is available online at http://diarsproject.github.io/DIARS/HomeDIARS.html. All the tutorials have been developed using two free and open source software (FOSS): R and GRASS GIS.
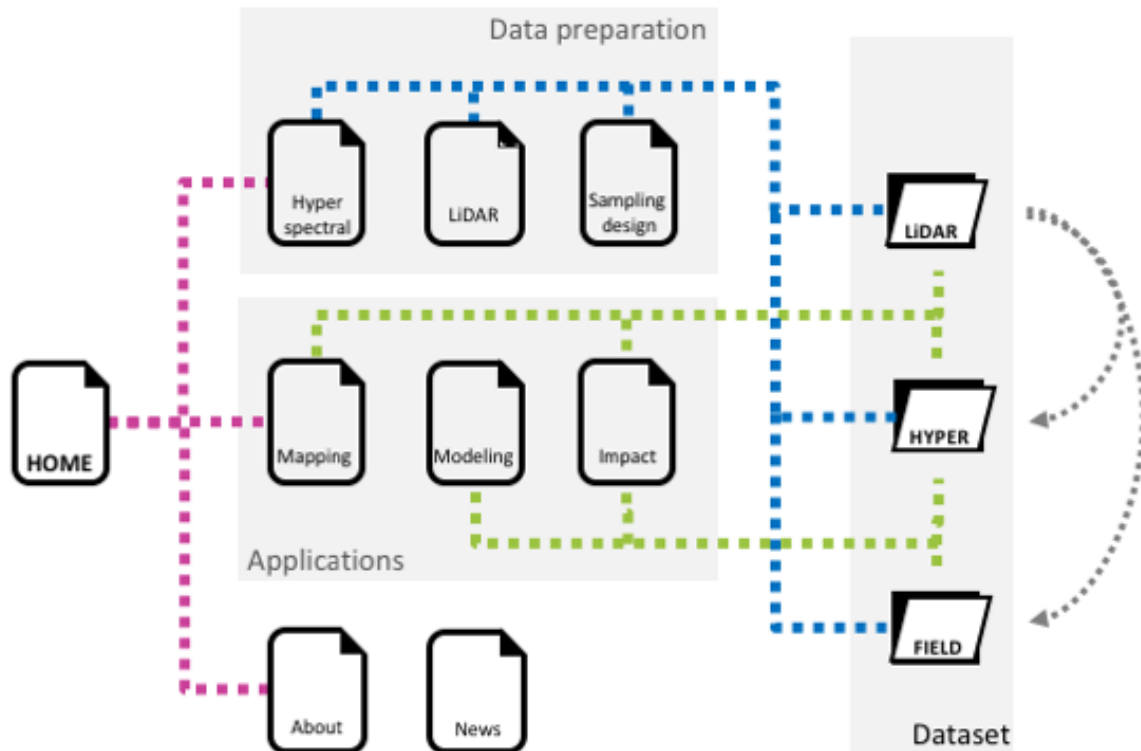
Figure 10: Structure of the DIARS toolbox. The dashed lines describe the dependencies among tutorials and the dataset.

Providing knowledge transfer and a hands-on training for ecologists, conservation biologists, policy makers and landscape managers across Europe (O5)

Finally 2 different knowledge transfer activities were organised. First, a hands-on training with the DIARS toolbox was organised within the EUFAR training course RS4FOREST EBV organised in the Bavarian Forest National Park and at DLR between July 3rd and July 14th 2017. Additionally also a workshop with local stakeholders was organized on Sylt on October 5th 2017. More information on this workshop can be found in the found in this video.

4.4. Follow up activities and plans for further exploitation of the results

- Scientific outreach: The scientific results will be as much as possible published into peer-reviewed journals. One more publication is planned.

- Open-source data and algorithms: The used algorithms and field/remote sensing data are distributed in the form of an open-source toolbox in R and GRASS GIS so other interested users can reproduce the methods.

- Follow-up projects: In order to ensure a continuation of DIARS, follow-up projects should further work on elaborating the insights gained within DIARS. Several pathways are possible, however one way of pursuing the work could be to work on operationalizing the mapping and modelling. This would imply a testing of the methodology for more species, in different ecosystems and over larger areas. The latter would require however the use of spaceborne remote sensing data, such as the recently launched superspectral Sentinel-2 satellite or upcoming hyperspectral sensors such as EnMAP.

- Become relevant for policy makers: The EU Regulation 1143/2014 on invasive species entered into force on 1 January 2015. This Regulation foresees three types of interventions: prevention, early detection and rapid eradication, and management. As the outcomes of DIARS can serve as input for all three of these interventions it is important to inform policy makers on the potential of the DIARS' tools and algorithms and be part of initiatives on the

implementation of this EU regulation. VITO is for instance involved in the recently started project Tracking Invasive Alien Species (TrIAS) in which a checklist on IAS for Belgium is made up and realized and potential distribution maps of IAS are generated.

5. Stakeholder engagement during project's life

1. Stakeholders' participation to project framing (including before the application)

Not applicable.

2. Provision of data by stakeholders; use of field/experiments allowed by stakeholders

During the fieldwork, collaboration with different stakeholders took place:

For fieldwork in Germany (cf. Sylt), we had a lot of contact with the "Naturschutzgemeinschaft Sylt e.V." and their executive director **Margit Ludwig-Schweikert**. When the project started, they were not aware of *Campylopus introflexus* invading the dunes of the Sylt island and thus were very interested in the project. They provided us with the permit to work in the area and gave us information on the applied management measures. The nature conservation authority of the district "Nordfriesland" delivered the permit. Furthermore, we got Natura 2000 habitat maps for the whole island of Sylt from the state agency for coastal protection, national parks and sea protection ("Landesbetrieb für Küstenschutz, Nationalpark und Meeresschutz") of Schleswig-Holstein. Maike Isermann, invasion biologist from the University of Bremen, was also involved and is co-author on one of the papers.

For fieldwork in France (cf. Compiègne), we collaborated with people from the "Office National des Forêts" (ONF). In particular, we benefited help from: **Jérôme Piat** who is responsible for the research and development activities at the ONF's territorial unit of Compiègne; **Manuel Nicolas** who manages the RENECOFOR research network at the ONF; and **Michel Leblanc** who was the former head of the ONF's territorial unit of Compiègne. The ONF's territorial unit of Compiègne provided us important data from the forest of Compiègne such as detailed maps of the: management units across the forest; stand types; stand ages; tree species composition at the stand level; road network inside the forest; forest management practices; and soil types. Most important, the ONF's territorial unit of Compiègne provided us LiDAR data covering the entire forest of Compiègne at very high resolution (up to 50 cm). Indeed, LiSAR data for the Compiègne study site was not acquired on the DIARS budget but via another project (SYLVANTIC) managed by the ONF and within which the French partner of the DIARS project (UPJV) is strongly involved. Therefore, LiDAR data across the forest of Compiègne belongs to the ONF but were made available within the DIARS project (cf. Attachment 1 in the signed Consortium Agreement: Background Included).

For fieldwork in the Belgium study sites, the "Natuurpunt" gave us permission to work in Averbode Bos en Heide (**Bram Cannaerts**), the "ANB" gave us permission to work in the Nature reserve of Pinnekensweijer (**Raf Verschueren**); and the "Defensie" gave us permission to work in Leopoldsburg Kamp Beverlo (**Erik Van Reckem**, Defensie 4RCI).

3. Involvement of stakeholders considered as research objects (eg. Participatory meetings use to assess biodiversity and service values by them)

Manuel Nicolas and **Jérôme Piat** from the ONF directly contributed during the leaf sampling campaign by shotgun at the Compiègne study site (FR). For instance, **Jérôme Piat** taught us how to perform the leaf canopy sampling by shotgun, a regular exercise that the ONF performs within the RENECOFOR network. But most important, this leaf sampling campaign by shotgun was entirely supervised by **Manuel Nicolas** and **Jérôme Piat** to avoid issues with the public during the fieldwork campaign. Indeed, the forest of Compiègne is very busy with people during the summer season (cf. tourists, cyclists, hikers, etc.) and this fieldwork campaign would not have been possible without the help and support of the ONF. We are thankful to the ONF for their active participation in the DIARS project. To perform the leaf sampling by shotgun, we also received a Model 4 permission for the

acquisition and use of a shotgun for scientific purposes by the governor of the Province of Vlaams Brabant (BE), **Lodewijk De Witte**, after positive advice by the local police of Leuven.

In addition to the significant contribution of the ONF to collect leaf samples across the forest of Compiègne, we also benefited advices and help from **Manuel Nicolas** when analysing the chemical contents of the leaf samples. For all these reasons, both **Manuel Nicolas** and **Jérôme Piat** were directly involved in the writing of two manuscripts led by the DIARS team but which involves data from the leaf sampling campaign in the forest of Compiègne.

4. Other meetings and activities (to be specified)

An international project steering committee consisting of two scientific experts and three stakeholders was set up. Two steering committee meetings were held in October 2015 (Leven, BE) and in December 2016 (Karlsruhe, DE).

The steering committee members are:

- Prof. Dr. **Ingolf Kühn** (expert in vegetation ecology with knowledge of remote sensing): Martin-Luther University Halle-Wittenberg, Helmholtz Centre for Environmental Research, UFZ Department Community Ecology (Germany);

- Dr. Ing. **Michael Förster** (expert in remote sensing of biodiversity): TU Berlin, Department of Landscape Architecture and Environmental Planning, Geoinformation in Environmental Planning Lab (Germany);

- Dr. **Sonia Vanderhoeven** (stakeholder with expertise in alien invasive plants): Belgian Biodiversity Platform (Belgium);

- Dr **Annett Frick** (stakeholder with expertise in vegetation ecology and remote sensing): LUP (Luftbild, Umwelt, Planung) (Germany);

- **Vincent Levy** (stakeholder with expertise in non-native invasive plants in northern France); Conservatoire Botanique National de Bailleul (CBNBL) - Antenne de Picardie (France).

6. Dissemination of results

6.1 List of scientific publications

2015:

1. Marcantonio M., Pareeth S., **Rocchini D.**, Metz M., **Garzón-López C.X.**, Neteler M. (2015). The integration of artificial night-time lights in landscape ecology: a remote sensing approach. *Ecological Complexity*, 22: 109-120

2. **Rocchini D.** (2015). Earth observation for ecosystems monitoring in space and time: a special issue in Remote Sensing. *Remote Sensing*, 7: 8102-8106

3. **Rocchini D.**, Andreo V., Forster M., **Garzón-López C.X.**, Gutierrez A. P., Gillespie T.W., Hauffe H.C., He K.S., Kleinschmit B., Mairota P., Marcantonio M., Metz M., Nagendra H., Pareeth S., Ponti L., Ricotta C., Rizzoli A., Schaab G., Zebisch M., Zorer R., Neteler M. (2015). Potential of remote sensing to predict species invasions: A modelling perspective. *Progress in Physical Geography*, 39: 283-309

4. **Rocchini D.**, Hernández-Stefanoni J.L., He K.S. (2015). Advancing species diversity estimate by remotely sensed proxies: a conceptual review. *Ecological Informatics*, 25: 22-28

2016:

5. Bacaro G., Altobelli A., Cameletti M., Ciccarelli D., Martellosa S., Palmer M.W., Ricotta C., **Rocchini D.**, Scheiner S.M., Tordonia E., Chiarucci A. (2016). Incorporating spatial autocorrelation in rarefaction methods: Implications for ecologists and conservation biologists. *Ecological Indicators*, 69: 233-238

6. Rubol S., Dutta T., **Rocchini D.** 2D visualization captures the local heterogeneity of oxidative metabolism across soils from diverse land-use. *Science of The Total Environment*, 572: 713-723

7. **Rocchini D.**, Boyd D.S., Féret J.B., Foody G.M., He K.S., Lausch A., Nagendra H., Wegmann M., Pettorelli N. (2016). Satellite remote sensing to monitor species diversity: potential and pitfalls. *Remote Sensing in Ecology and Conservation*, 2: 25-36

2017:

8. **Aerts R.**, **Ewald M.**, Nicolas M., Piat J., **Skowronek S.**, **Lenoir J.**, **Hattab T.**, **Garzón-López C.X.**, **Feilhauer H.**, **Schmidtlein S.**, **Rocchini D.**, **Decocq G.**, **Somers B.**, **Van De Kerchove R.**, Denef K., **Honnay O.** (2017) Invasion by the alien tree *Prunus serotina* alters ecosystem functions in a temperate deciduous forest. *Frontiers in Plant Science*, 8: 179

9. Bacaro G., Altobelli A., Cameletti M., Ciccarelli D., Martellosa S., Palmer M.W., Ricotta C., **Rocchini D.**, Scheiner S.M., Tordonia E., Chiarucci A. (2016). Incorporating spatial autocorrelation in rarefaction methods: Implications for ecologists and conservation biologists. *Ecological Indicators*, 69: 233-238

10. **Hattab T.**, **Garzón-López C.X.**, **Ewald M.**, **Skowronek S.**, **Aerts R.**, Horen H., Brasseur B., Gallet-Moron E., Spicher F., Decocq G., **Feilhauer H.**, **Honnay O.**, Kempeneers P., **Schmidtlein S.**, **Somers B.**, **Van De Kerchove R.**, **Rocchini D.**, **Lenoir J.** (2017). A unified framework to model the potential and realized distributions of invasive species within the invaded range. *Diversity and Distribution*, 23: 806-819

11. **Rocchini D.**, Petras V., Petrasova A., Chemin Y., Ricotta C., Frigeri A., Landa M., Marcantonio M., Bastin L., Metz M., Delucchi L., Neteler M. (In press). Spatio-ecological complexity measures in GRASS GIS. *Computers & Geosciences*

12. Rugani B., **Rocchini D.** (2017). Boosting the use of spectral heterogeneity in the impact assessment of agricultural land use on biodiversity. *Journal of Cleaner Production*, 140: 516-524

13. **Skowronek S.**, **Ewald M.**, Isermann M., **Van De Kerchove R.**, **Lenoir J.**, **Aerts R.**, Warrie J., **Hattab T.**, **Honnay O.**, **Schmidtlein S.**, **Rocchini D.**, **Somers B.**, **Feilhauer H.** (2017). Mapping an invasive bryophyte species using hyperspectral remote sensing data. *Biological Invasions*, 19: 239-254

14. **Skowronek S.**, **Asner G.P.**, **Feilhauer H.** (2017). Performance of one-class classifiers for invasive species mapping using airborne imaging spectroscopy. *Ecological Informatics*, 37: 66-76

2018

15. **Ewald M.**, **Aerts R.**, **Lenoir J.**, Fassnacht F.E., Nicolas M., **Skowronek S.**, Piat J., **Honnay O.**, **Garzón-López C.X.**, **Feilhauer H.**, **Van De Kerchove R.**, **Somers B.**, **Hattab T.**, **Rocchini D.**, **Schmidtlein S.** (2018). LiDAR derived forest structure data improves predictions of leaf N and P concentrations from imaging spectroscopy. Remote Sensing of Environment, 211:13-25

16. **Ewald M.**, **Skowronek S.**, **Aerts R.**, Dolos K., **Lenoir J.**, Nicolas M., Warrie J., **Hattab T.**, **Feilhauer H.**, **Honnay O.**, **Garzón-López C.X.**, Decocq G., **Van De Kerchove R.**, **Somers B.**, **Rocchini D.**, **Schmidtlein S.** (In preparation). Analyzing remotely sensed structural and chemical canopy tratis of a forest invaded by Prunus serotina over multiple spatial scales. Biological Invasions, 1-15,

17. *Garzón-López C.X.*, *Hattab T.*, *Skowronek S.*, *Ewald M.*, *Aerts R.*, *Feilhauer H.*, *Honnay O.*, Decocq G., *Van De Kerchove R.*, *Somers B.*, *Schmidtlein S.*, Rocchini D., *Lenoir J.* (In preparation). The DIARS toolbox: a spatially explicit approach to monitor alien plant invasions through remote sensing. Research Ideas and Outcomes, e25301

18. **Skowronek S.**, **Van De Kerchove R.**, **Ewald M.**, **Lenoir J.**, **Aerts R.**, Warrie J., Schiefer F., Rombouts B., **Hattab T.**, **Honnay O.**, **Schmidtlein S.**, **Rocchini D.**, **Somers B.**, **Feilhauer H.**, (2018). Transferability of species distribution models for the detection of an invasive alien bryophyte using imaging spectroscopy data. International Journal of Applied Earth Observation and Geoinformation, 68:61-72

In preparation (non-exhaustive):

19. **Hattab T.**, **Garzón-López C.X.**, **Ewald M.**, **Skowronek S.**, **Aerts R.**, **Feilhauer H.**, **Honnay O.**, **Schmidtlein S.**, **Somers B.**, **Van De Kerchove R.**, **Rocchini D.**, **Lenoir J.** (In preparation). Spatially explicit demographic modelling of *Prunus serotina* at very high resolution. *Remote Sensing in Ecology and Conservation*

6.2. Dissemination of results to scientists and scientific organisations (0,5 page max)

Oral presentations:

1. Kempeneers P., **Van De Kerchove R.** (2014). DIARS - Detection of invasive plant species and assessment of their impact on ecosystem properties through remote sensing. *BiodivERsA kick-off meeting for the 2012-2013 funded projects*, October 3rd 2014, Paris, France
2. **Van De Kerchove R.**, **Skowronek S.**, **Ewald M.**, **Aerts R.**, **Hattab T.**, Warrie J., **Feilhauer H.**, **Somers B.**, **Schmidtlein S.**, **Lenoir J.**, **Rocchini D.**, **Honnay O.**, Kempeneers P. (2015). DIARS - Detection of invasive plant species and assessment of their impact on ecosystem properties through remote sensing. *Belgian Forum on Invasive Species – What's up with invasive alien species (IAS)*, April 2nd 2015, Brussels, Belgium
3. **Skowronek S.**, **Ewald M.**, **Aerts R.**, Warrie J., **Van De Kerchove R.**, Kempeneers P., **Honnay O.**, **Lenoir J.**, **Somers B.**, **Schmidtlein S.**, **Feilhauer H.** (2015). Invasive Pflanzenarten auf der Insel Sylt und ihre Erfassung mithilfe von Fernerkundungsdaten. *AK Biogeo*, May 7th-8th 2015, Basel, Switzerland.
4. **Van De Kerchove R.**, **Skowronek S.**, **Ewald M.**, **Aerts R.**, **Hattab T.**, **Feilhauer H.**, **Somers B.**, **Schmidtlein S.**, **Lenoir J.**, **Rocchini D.**, **Honnay O.**, Kempeneers P. (2015). DIARS: Detection of invasive plant species and assessment of their impact on ecosystem properties through remote sensing. *BiodivERsA workshop*, June 23rd-24th 2015, Brussels, Belgium
5. **Hattab T.**, **Rocchini D.**, **Somers B.**, Gallet-Moron E., Decocq G., **Feilhauer H.**, Warrie J., **Ewald M.**, **Honnay O.**, Kempeneers P., **Aerts R.**, **Van De Kerchove R.**, **Skowronek S.**, **Schmidtlein S.**, **Lenoir J.** (2015). Modelling of habitat suitability and population dynamics of an invasive plant with advanced remote sensing data. *58th Annual Symposium of the International Association for Vegetation Science*, July 19th-24th 2015, Brno, Czech Republic
6. **Skowronek S.**, **Ewald M.**, **Aerts R.**, Warrie J., **Van De Kerchove R.**, Kempeneers P., **Honnay O.**, **Lenoir J.**, **Somers B.**, **Schmidtlein S.**, **Feilhauer H.** (2015). Mapping of invasive plant species on the island of Sylt using hyperspectral data. *58th Annual Symposium of the International Association for Vegetation Science*, July 19th-24th 2015, Brno, Czech Republic
7. **Ewald M.**, **Skowronek S.**, **Aerts R.**, Warrie J., **Van De Kerchove R.**, Kempeneers P., **Honnay O.**, **Lenoir J.**, **Somers B.**, **Feilhauer H.**, **Schmidtlein S.** (2015). Assessing the impacts of invasive plants on ecosystems through remote sensing. *GfOe Annual Meeting 2015*, August 31st-September 4th 2015, Göttingen, Germany
8. **Skowronek S.**, **Ewald M.**, **Aerts R.**, Warrie J., **Van De Kerchove R.**, Kempeneers P., **Honnay O.**, **Lenoir J.**, **Somers B.**, **Schmidtlein S.**, **Feilhauer H.** (2015). Mapping of two invasive plant species on the island of Sylt in northern Germany using airborne hyperspectral and LIDAR data. *The International Conference Ecology and Management of Alien Plant Invasions (EMAPi)*, September 20th-24th 2015, Hawaii, United States
9. **Ewald M.**, **Skowronek S.**, **Aerts R.**, **Van De Kerchove R.**, Kempeneers P., **Honnay O.**, **Lenoir J.**, **Hattab T.**, **Somers B.**, **Feilhauer H.**, **Roccini D.**, **Schmidtlein S.** (2016). Using

remote sensing to quantify the ecosystem impact of invasive plant species. *GEO BON Open Science Conference 2016*, July 4th-8th 2016, Leipzig, Germany

10. **Van De Kerchove, R., Skowronek, S., Ewald, M., Aerts, R., Hattab, T., Warrie, J., Feilhauer, H., Somers, B., Schmidtlein, S., Lenoir, J., Rocchini, D., Honnay, O., Kempeneers, P.** (2017). DIARS - Detection of invasive plant species and assessment of their impact on ecosystem properties through remote sensing. *2nd International Conference on Airborne Research for the Environment*, July 10th-13th 2017, Oberpfaffenhofen, Germany.

Posters:

11. **Van De Kerchove R.**, Kempeneers P., **Feilhauer H.**, **Lenoir J.**, **Rocchini D.**, **Schmidtlein S.**, **Honnay O.**, **Asner G.**, **Somers B.** (2014). Detection of invasive plant species and assessment of their impact on ecosystem properties through remote sensing (DIARS). *One-day Benelux conference on invasive specie*s, April 2nd 2014, Ghent, Belgium

12. **Van De Kerchove R.**, **Skowronek S.**, **Ewald M.**, **Aerts R.**, **Hattab T.**, Warrie J., **Feilhauer H.**, **Somers B.**, **Schmidtlein S.**, **Lenoir J.**, **Rocchini D.**, **Honnay O.**, Kempeneers P. (2015). Detection of invasive plant species and assessment of their impact on ecosystem properties through remote sensing - the DIARS project. *Empowering Biodiversity Research Conference*, May 20th 2015, Brussels, Belgium

13. **Skowronek S.**, **Ewald M.**, **Aerts R.**, Warrie J., **Van De Kerchove R.**, Kempeneers P., **Honnay O.**, **Lenoir J.**, **Hattab T.**, **Somers B.**, **Schmidtlein S.**, **Rocchini D.**, **Asner G.**, **Feilhauer H.** (2016). Mapping invasive plant species with a combination of field and remote sensing data. *AGU fall meeting 2016*, December 14th-18th 2015, San Francisco, United States

14. **Hattab T.**, **Rocchini D.**, Kempeneers P., **Van De Kerchove R.**, **Somers B.**, **Honnay O.**, **Aerts R.**, Warrie J., **Feilhauer H.**, **Skowronek S.**, **Schmidtlein S.**, **Ewald M.**, Gallet-Moron E., Decocq G., **Lenoir J.** (2016). Integrating advanced remote sensing data into a multi-scale Species Distribution Model (SDM) coupled with a population model to predict the invasion dynamic of a non-native plant. *Species On The Move (SOTM) 2016*, February 9th-12th 2016, Hobart, Australia

15. **Skowronek S.**, **Ewald M.**, **Aerts R.**, Warrie J., **Van De Kerchove R.**, Kempeneers P., **Honnay O.**, **Lenoir J**., **Hattab T.**, **Somers B.**, **Schmidtlein S.**, **Rocchini D.**, **Asner G.**, **Feilhauer H.** (2016). Mapping invasive plant species with a combination of field and remote sensing data. *ESA Living Planet Symposium 2016*, May 9th-13th 2016, Prague, Czech Republic

16. Sammet F., **Skowronek S., Aerts R., Asner G., Ewald M., Hattab T., Honnay O., Kempeneers P., Lenoir J., Rocchini D., Schmidtlein S., Somers B., Van De Kerchove R., Warrie J., Feilhauer H.** (2016). Mapping the invasive plant Rosa rugosa with hyperspectral data and One-Class Support Vector Machines. *ESA Living Planet Symposium 2016*, May 9th-13th 2016, Prague, Czech Republic

Other initiatives:

17. *One-day Benelux conference on invasive species organized by among others* **Ben Somers** *and* **Olivier Honnay**, April 2nd 2014, Ghent, Belgium

18. *Special session on remote sensing for vegetation science convened by* **Hannes Feilhauer**, **Duccio Rocchini** & **Sebastian Schmidtlein** *at the 58th Annual Symposium of the International Association for Vegetation Science*, July 19th-24th 2015, Brno, Czech Republic

6.3 List of dissemination activities with stakeholders

Oral presentations:

1. **Lenoir J.** (2017). L'élaboration d'un modèle de distribution de *Prunus serotina* à l'aide de données LiDAR. *Conférence grand public organisée par l'Office National des Forêts (ONF) sur les utilisations du LiDAR en forêt domaniale de Compiègne*, 2 Février 2017, Compiègne, France

6.4 Dissemination of results to stakeholders (0,5 page max)

Newspapers and newsletters:

1. An article entitled "*Planten screenen vanuit de ruimte*" presenting the DIARS project was written by the newspaper "Metro", a local Belgian newspaper, and published on October 27th 2014

2. An article on our work in Sylt was written for the yearly newsletter of the "Naturschutzgemeinschaft Sylt e.V.". This article can now be found online at http://www.naturschutz-sylt.de/wp-content/uploads/2013/01/Jahresbericht2014_farbe.pdf

Information/Technology Transfer

3. Ahands-on training with the DIARS toolbox was organised within the EUFAR training course RS4FOREST EBV organised in the Bavarian Forest National Park and at DLR between July 3rd and July 14th 2017.

4. a workshop with local stakeholders was organized on Sylt on October 5th 2017. More information on this workshop can be found in the found in this video.

Websites and social networks:

5. A project website dedicated to the DIARS project can be found at http://diars.vgt.vito.be/

6. A Twitter account (@project_DIARS) has been created to advertise outcomes and key findings from the DIARS project but information on the project is also popularized through the twitter accounts of Ruben Van De Kerchove (@RubenVDKerchove), Jonathan Lenoir (@EkoLogIt), Raf Aerts (@rafaerts) and Duccio Rocchini (@ducciorocchini)

Education projects:

7. Master thesis of **Veerle Herssens** under the supervision of **Ben Somers** and **Olivier Honnay** (2014) "*Detectie en impactbepaling van invasieve plantensoorten op basis van hyperspectrale remote sensing*". KU Leuven Master Dissertation, Leuven, Belgium

8. Master thesis of **Jens Warrie** under the supervision of Raf Aerts, **Ben Sommers** and **Olivier Honnay** (2015) "*Impact en detectie van invasieve bryofyten met behulp van hyperspectrale remote sensing. Een gevalstudie van Campylopus introflexus*". KU Leuven Master Dissertation, Leuven, Belgium

9. Master thesis of **Bjorn Rombouts** under the supervision of **Ben Somers**, **Ruben Van De Kerchove** and **Raf Aerts** (2016) "*Detection of an invasive bryophyte using imaging spectroscopy*". KU Leuven Master Dissertation, Leuven, Belgium

10. Master thesis of **Franziska Sammet** under the supervision of **Hannes Feilhauer** and **Sandra Skowronek** (2016) "*Mapping the invasive species Rosa rugosa with hyperspectral data and One-Class Support Vector Machines*". FAU Erlangen-Nürnberg, Erlangen, Germany

11. Bachelor thesis of **Felix Schiefer** under the supervision of **Hannes Feilhaue**r and **Sandra Skowronek** (2015) "*Kartierung der invasiven Moosart Campylopus introflexus mittels hyperspektraler Fernerkundungsdaten*". FAU Erlangen-Nürnberg, Erlangen, Germany

12. Bachelor thesis of **Luisa Mayer** under the supervision of **Michael Ewald** and **Sebastian Schmidtlein** (2015) "*Der Einfluss von Prunus serotina auf Vegetation und Bodeneigenschaften*". Karlsruhe Institut of Technology, Karlsruhe, Germany

7 Global Impact assessment indicators

7.1 Impact statement

Many important results have emerged from DIARS and valuation is still ongoing at the time of writing this final report. Among the results published, some have already retain the attention of the press in Germany and in Belgium (cf. local newspapers). Importantly, the DIARS consortium produced a new R package called iSDM which was advertised through social networks (Twitter®, Facebook®) and through the accompanying research paper which was accepted in Diversity and Distribution, one of the top journals in biodiversity conservation and ecology. So far, this particular paper in Diversity and Distribution has already received significant attention (see its Altmetric score), suggesting a potential

for a strong impact on the scientific community and beyond. The actions for transferring the results and knowledge produced by DIARS to stakeholders were quite successful and more actions have been planned (cf. further promotion of the DIARS toolbox).

7.2 Synthetic figures for the project publications (including interactions with stakeholders)

A total of 18 papers have already been published and 1 is still in preparation (listed above). Among the 18 papers published or in early view, 9 have an impact factor >3.

Analysis of the *project* publications:

Scientific Journal	Number	Impact Factor (2015)
Remote Sensing of Environment	1	5.881
Journal of Cleaner Production	1	4.959
Diversity and Distribution	1	4.566
Frontiers in Plant Science	1	4.495
Science of The Total Environment	1	3.976
International Journal of Applied Earth Observation and Geoinformation	1	3.798
Ecological Indicators	2	3.190
Remote Sensing	1	3.036
Biological Invasions	2	2.855
Progress in Physical Geography	1	2.728
Computers & Geosciences	1	2.474
Ecological Complexity	1	1.797
Ecological Informatics	2	1.683
Remote Sensing in Ecology and Conservation	1	Not yet
Research Ideas and Outcomes	1	Not yet

International dimension and multi-partnership for publications

Numbers followed by the # symbol in the table below refer to the publications listed in section 6.1 (cf. "List of scientific publications").

=		Multi-partner publications	Number of partners in multi-partner publication	Number of European countries involved in multi-partner publication	Single-partner publications
International	**Peer-reviewed journals (cf. numbers in the list above)**	#8 #10 #13 #14 #15 #16 #17 #18	6 6 6 2 6 6 6 6	4 4 4 1 4 4 4 4	#1 #2 #3 #4 #5 #6 #7 #9 #11 #12
	Books or chapters in books				
	Communications (conferences) (cf. numbers in the list above)	#2 #3 #4 #5 #6 #7 #8 #9 #10	6 6 6 6 6 6 6 6 6	4 4 4 4 4 4 4 4 4	#1
Country xxx (partner xxx)	**Peer-reviewed journals**				
	Books or chapters in books				
	Communications (conferences)				
Outreach initiatives including interactions with stakeholders	**Popularization articles**				
	Popularization conferences				
	Others				

7.3. Other scientific valorisation factors

	Number, years and comments (Actual or likely valorizations)
International patents obtained	
International patents pending	
National patents obtained	
National patents pending	
Operating licences (obtained / transferred)	
Software and any other prototype	iSDM (https://cran.r-project.org/web/packages/iSDM/)

Company creations or spin-offs	
New collaborative projects	
Scientific symposiums	One-day Benelux conference on invasive species organized by among others Ben Somers and Olivier Honnay, April 2nd 2014, Ghent, Belgium

Special session on remote sensing for vegetation science convened by Hannes Feilhauer, Duccio Rocchini & Sebastian Schmidtlein at the 58th Annual Symposium of the International Association for Vegetation Science, July 19th-24th 2015, Brno, Czech Republic |
| **Others (specify)** | |

7.4. Assessment and follow-up of personnel recruited on fixed-term contracts (excluding interns)

Identification			Before recruitment for the project			Recruitment for the project				After the project			
Surname and first name	Sex M/F	E-mail address	Last diploma	Country of studies	Prior professional experience, including post-docs (years)	Partner who hired the person (Organisation and Country)	Position in the project (1)	Duration of missions (months) (2)	End date of mission on project	Professional future (3)	Type of employer (4)	Type of employment (5)	Promotion of professional experience (6)
HATTAB Tarek	M	hattab.tarek@gmail.com	PhD	Tunisia and France	3	UPJV (FR)	Post-doctoral	24 @100%	December 31st 2016	Open-ended contract	Public institution	Researcher	Yes
GARZON-LOPEZ Carol Ximena	F	c.x.garzon@gmail.com	PhD	Columbia and the Netherlands	5	UPJV (FR)	Post-doctoral	12 @100%	December 31st 2016	Post-doctoral position abroad	University	Lecturer-researcher	Yes
AERTS Raf	M	raf.aerts@kuleuven.be	PhD	Belgium	15	KUL (BE)	Post-doctoral	30 @80%	May 8th 2016	Post-doctoral researcher	Public institution	Researcher	Yes
Ewald, Michael	M	michael.ewald@kit.edu	M.Sc.	Germany	2	KIT (DE)	Doctoral student	36 @100%	April 30th 2017	Post-doctoral researcher	Public institution	Researcher	Yes
Sandra Skowronek	F	sandra.skowronek@fau.de	M.Sc.	Germany		FAU (DE)	Doctoral student	36 @100%	December 31st 2016	Open-ended contract	Public institution	Researcher	Yes

7.5. Data Management and timeline for open access