IPROMO

INTERNATIONAL PROGRAMME ON RESEARCH AND TRAINING ON SUSTAINABLE MANAGEMENT OF MOUNTAIN AREAS

Mountain Partnership
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UNIVERSITÀ DEGLI STUDI DI TORINO

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Food and Agriculture Organization of the United Nations

2019 SUMMER SCHOOL

Landscape approach for enhancing mountain resilience

Exploiting satellite remote sensing to understand landscape-scale forest dynamics with a focus on forest fires

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Presentation outline

1. **Introduction:** landscape-scale forest dynamics and Earth observation satellites for forest ecologists

2. **Case study 1:** forest recovery dynamics in stand-replacing wildfires of central Apennines (Italy) derived from Landsat time series

3. **Case study 2:** burn severity mapping by integrating remote sensing and field assessment: the big forest fires in Northwestern Italy during autumn 2017

4. **Case study 3:** exploring long-term fire-related dynamics in coniferous forests dominated by Scots pine (*Pinus sylvestris*) using Landsat time series and field data in the Aosta Valley (Italy)

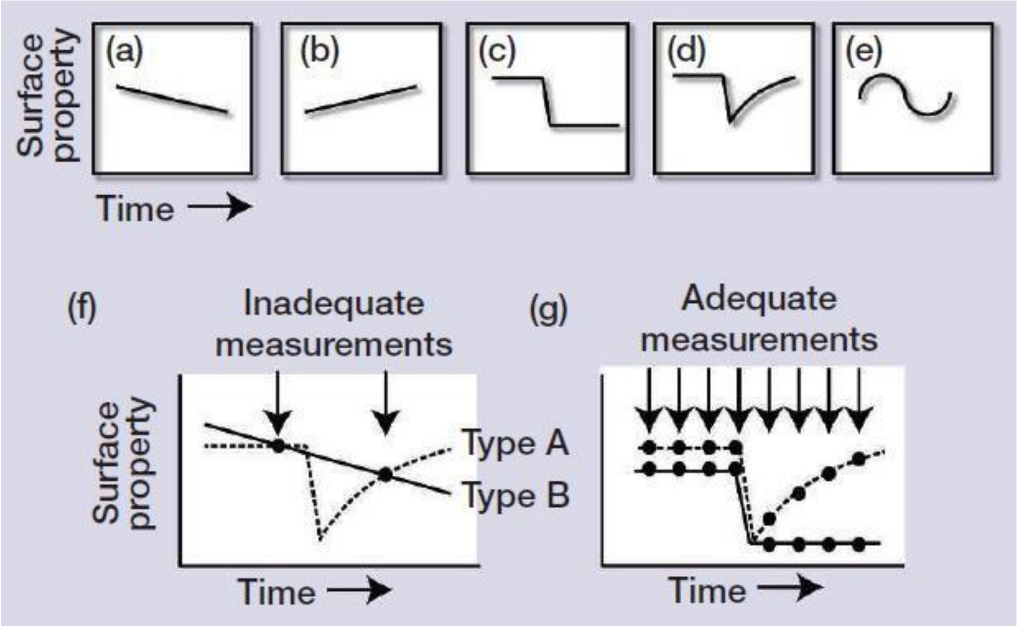
How forest ecosystems change

- Ecological processes alter several biophysical quantities of forest ecosystems
- Changes can be gradual (a, b), abrupt (c, d) or cyclical (e)
- Underlying processes can be characterized and understood if observations are adequately taken
- Trajectories of biophysical quantities can be conceptualized using mathematical response functions

Canopy closure

Biomass level

Vertical structure



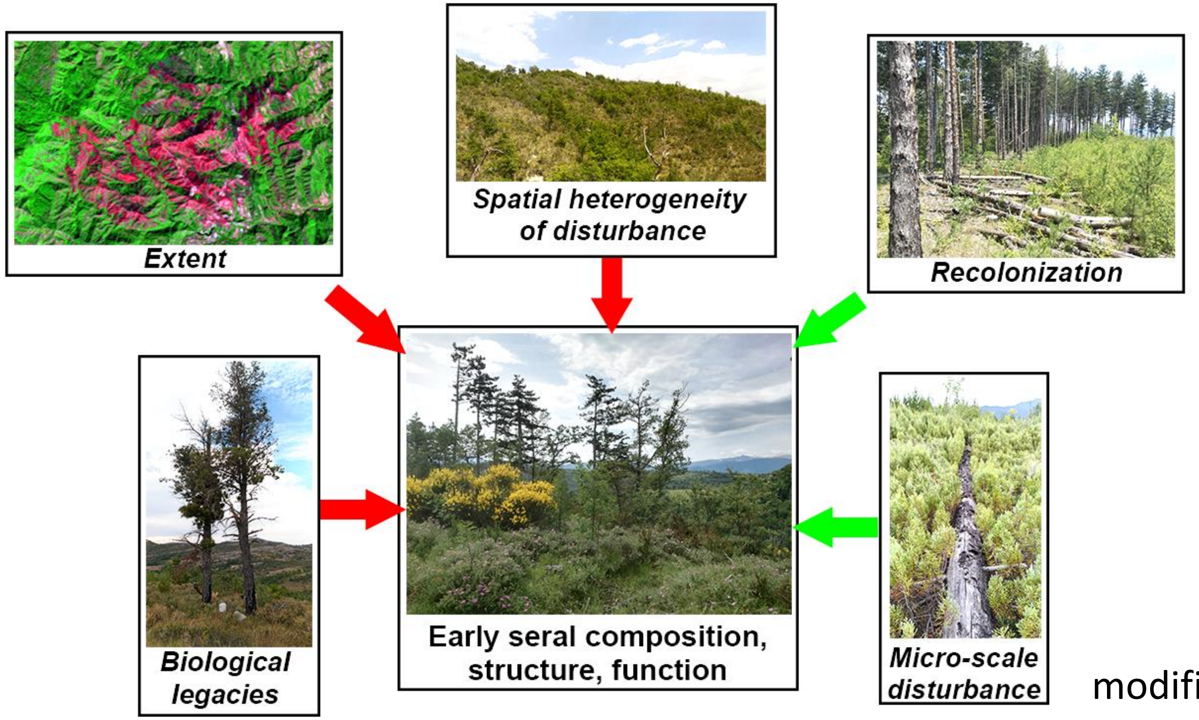
Kennedy *et al. 2014*

Post-fire forest recovery

- The process of re-establishment of tree cover (aka stand re-initiation) and associated ecological functions on disturbed sites (Scheller & Swanson 2015)

- Post-fire forest recovery is a gradual process following an abrupt change

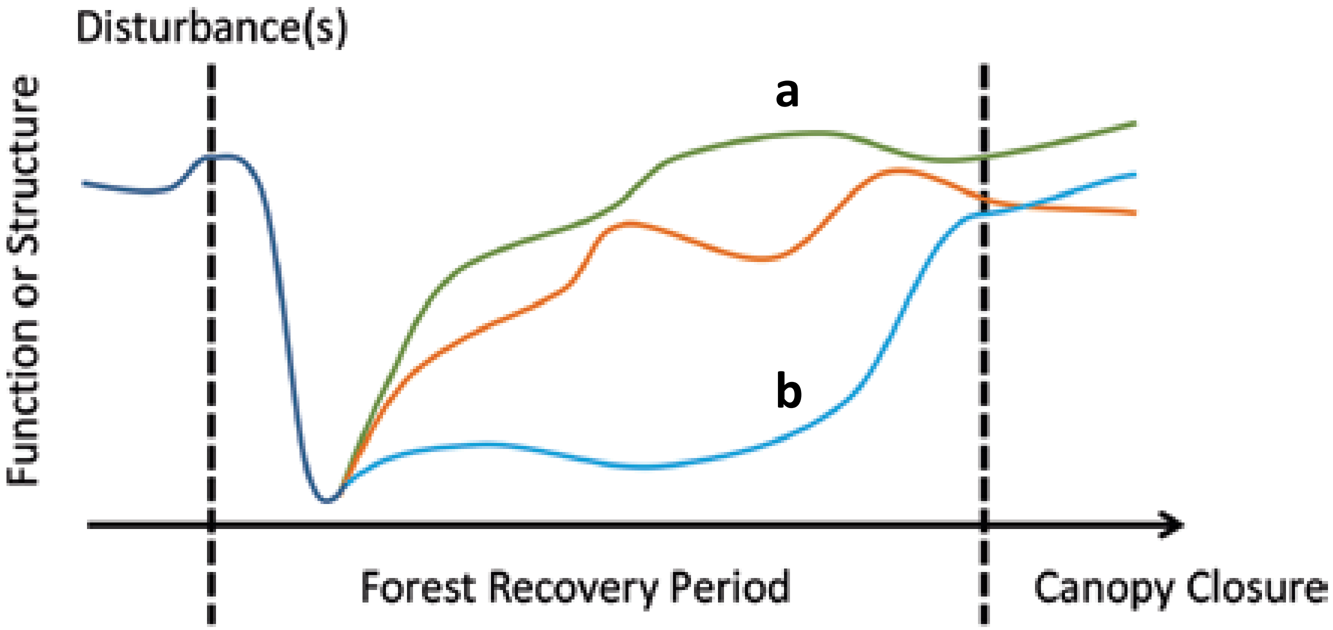
- Composition, structure and function of early stages of secondary succession are determined by interactions between disturbance-behavior factors and post-disturbance processes



modified from Scheller & Swanson 2015

Post-fire forest recovery

- High degrees of complexity characterize the initial post-fire conditions and are generated by modified fluxes of energy and material in the forested landscape
- Burned forest stands may follow many different long-term trajectories leading either to gradual (a) or delayed (b) recovery, which success is evaluated through tree canopy closure



Scheller & Swanson 2015

Post-fire forest recovery

- Four main drivers of the process: biological legacies, tree regeneration, altered forest fluxes (carbon, nitrogen, water) and post-fire management interventions

Biological legacies

Living and dead individuals belonging to the pre-disturbance forest ecosystem

Tree regeneration

Density, composition and patterns of tree regeneration influenced by fire behaviour

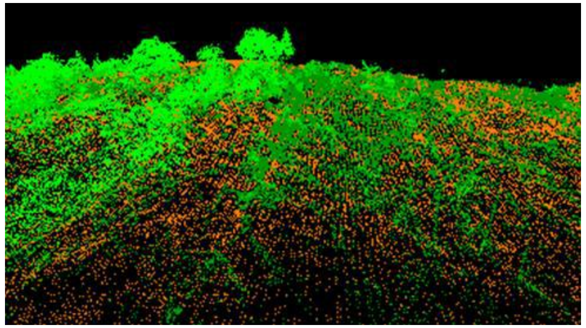
Forest recovery assessment

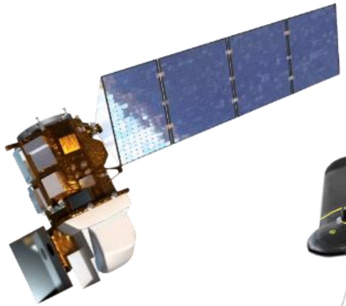
Field surveys (plot to stand scale)

- **Forest regeneration structure and composition**
- **Field sensors** for microclimate conditions (soil moisture and temperature)
- **Validation and intergration** with remote sensing products (e.g. land cover maps, biophysical parameters)

Remote sensing (stand to global scale)

- **Platforms:** aircrafts, satellites and UAVs
- **Data:** aerial ortophotos, multispectral and hyperspectral imagery, LiDAR
- **Tecniques:** land cover classification, time series, spectral vegetation indices, canopy heigth models





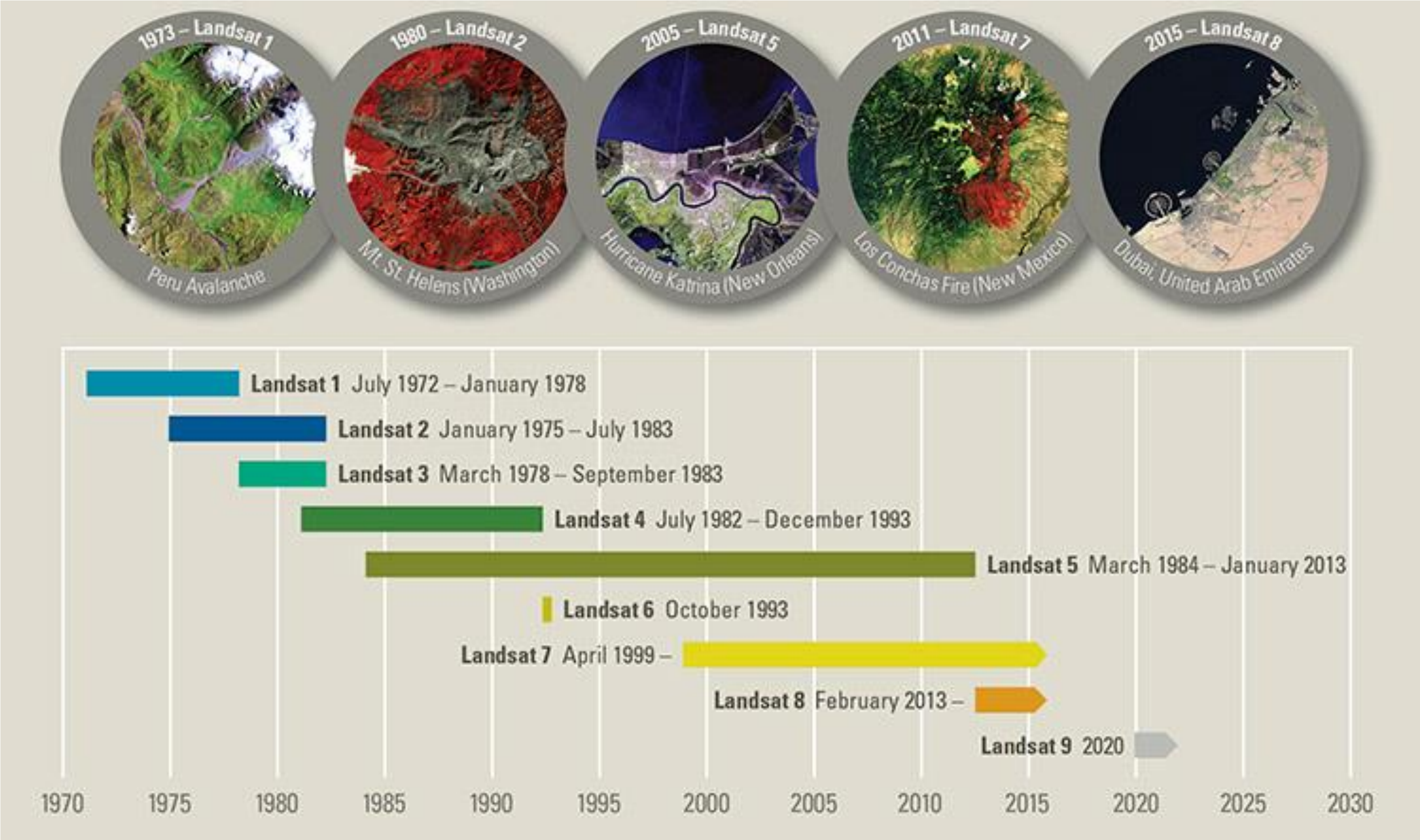
Earth observation satellites for forest ecologists

- **Landsat Missions (NASA/USGS)**: since 1972, Landsat satellites have continuously acquired space-based images of the Earth's land surface

- Up to 8 days revisiting time with 2 Landsat satellites (16 days with a single satellite)

- Spatial (30m) and radiometric resolutions are well suited for forest ecology

- **Landsat Science Products** from USGS provide length, consistency, and continuity to study Earth's surface processes



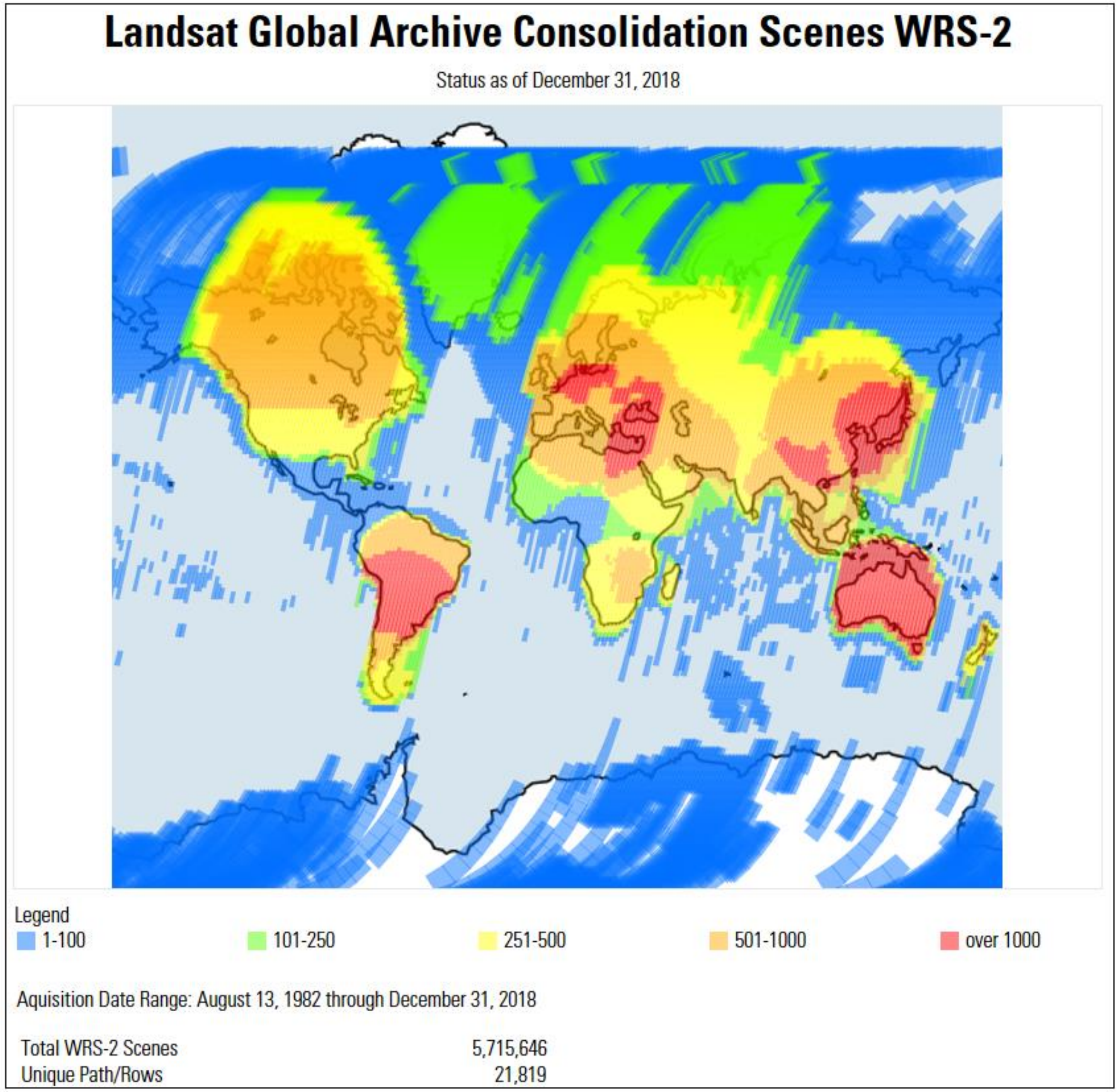
https://www.usgs.gov/media/images/landsat-missions-timeline

Earth observation satellites for forest ecologists

- The map displays Landsat 7 ETM+, Landsat 4-5 TM, and Landsat 4-5 MSS scenes received between 1982 and 2018

- Landsat scenes received from International Ground Stations range from 500 to 1000 for most of Earth's land areas

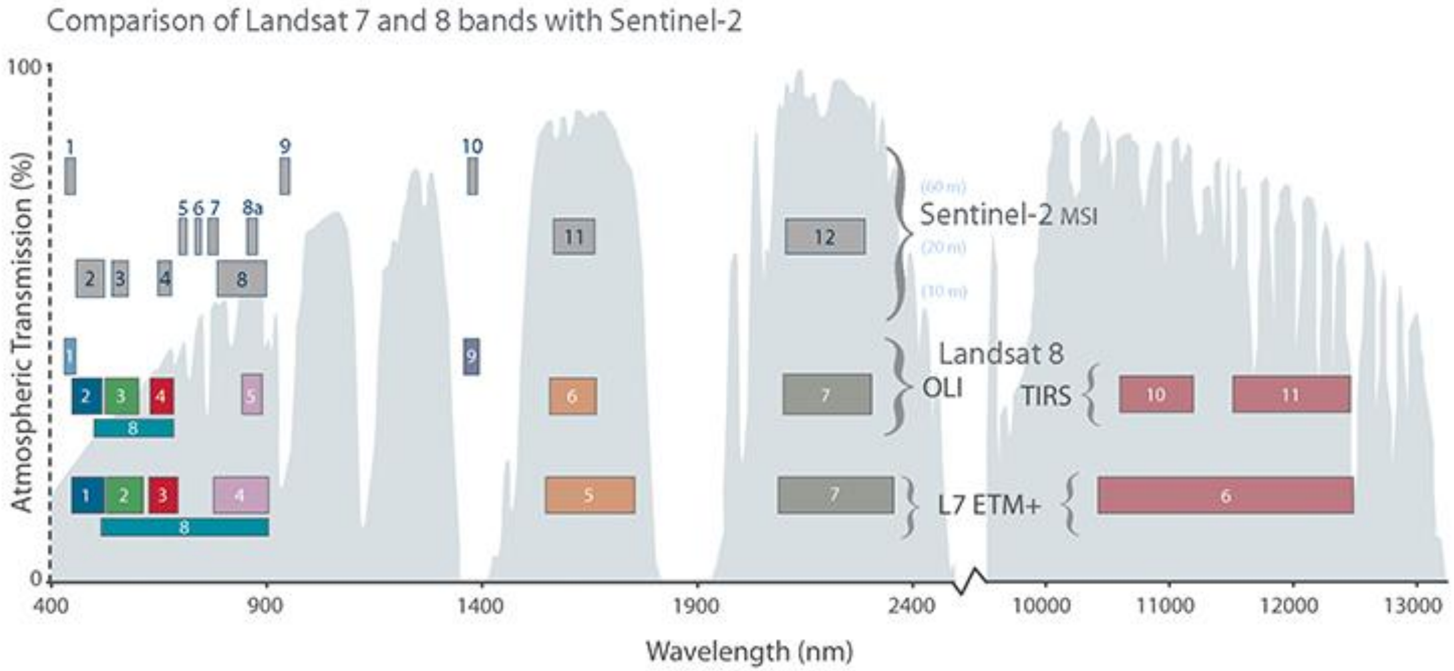
- **Landsat Level-2 Science products** (Collection 1):
  - ➢ Earth's surface reflectance
  - ➢ surface reflectance-derived Spectral indices
  - ➢ surface temperature (Kelvin)



https://www.usgs.gov/media/images/landsat-global-archive-consolidation-wrs-2-scenes

Earth observation satellites for forest ecologists

- **Sentinel-2 mission (ESA):** Sentinel-2A launched on June 2015, Sentinel-2B March 2017
- MSI sensor onboard: 13 spectral bands with 10m (4), 20m (6), 60m (3) spatial resolution
- 5 days revisiting time using both S2A and S2B satellites
- Spectral consistency between Sentinel-2 and Landsat 8 sensors allowed to generate the Harmonized Landsat Sentinel-2 dataset (https://hls.gsfc.nasa.gov)



https://landsat.gsfc.nasa.gov/sentinel-2a-launches-our-compliments-our-complements/

CASE STUDY 1

Forest recovery dynamics in stand-replacing wildfires of central Apennines (Italy) derived from Landsat time series

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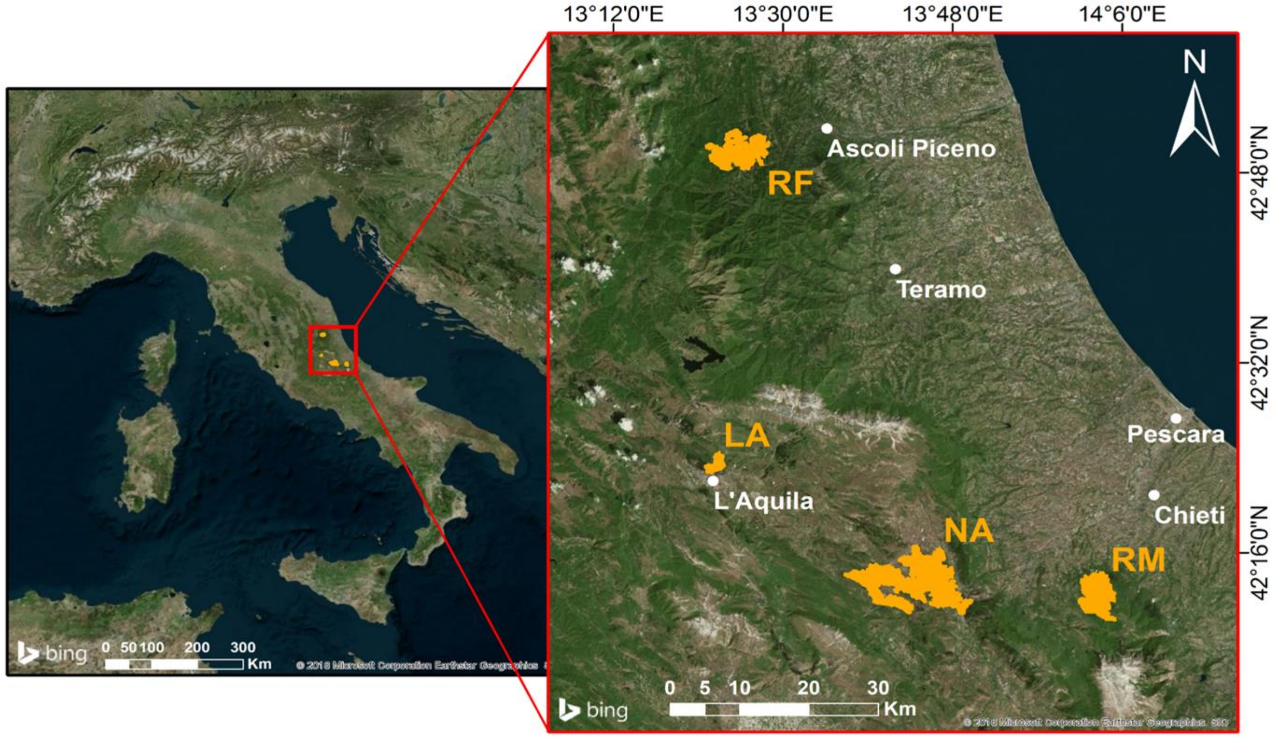
Study areas and research objectives

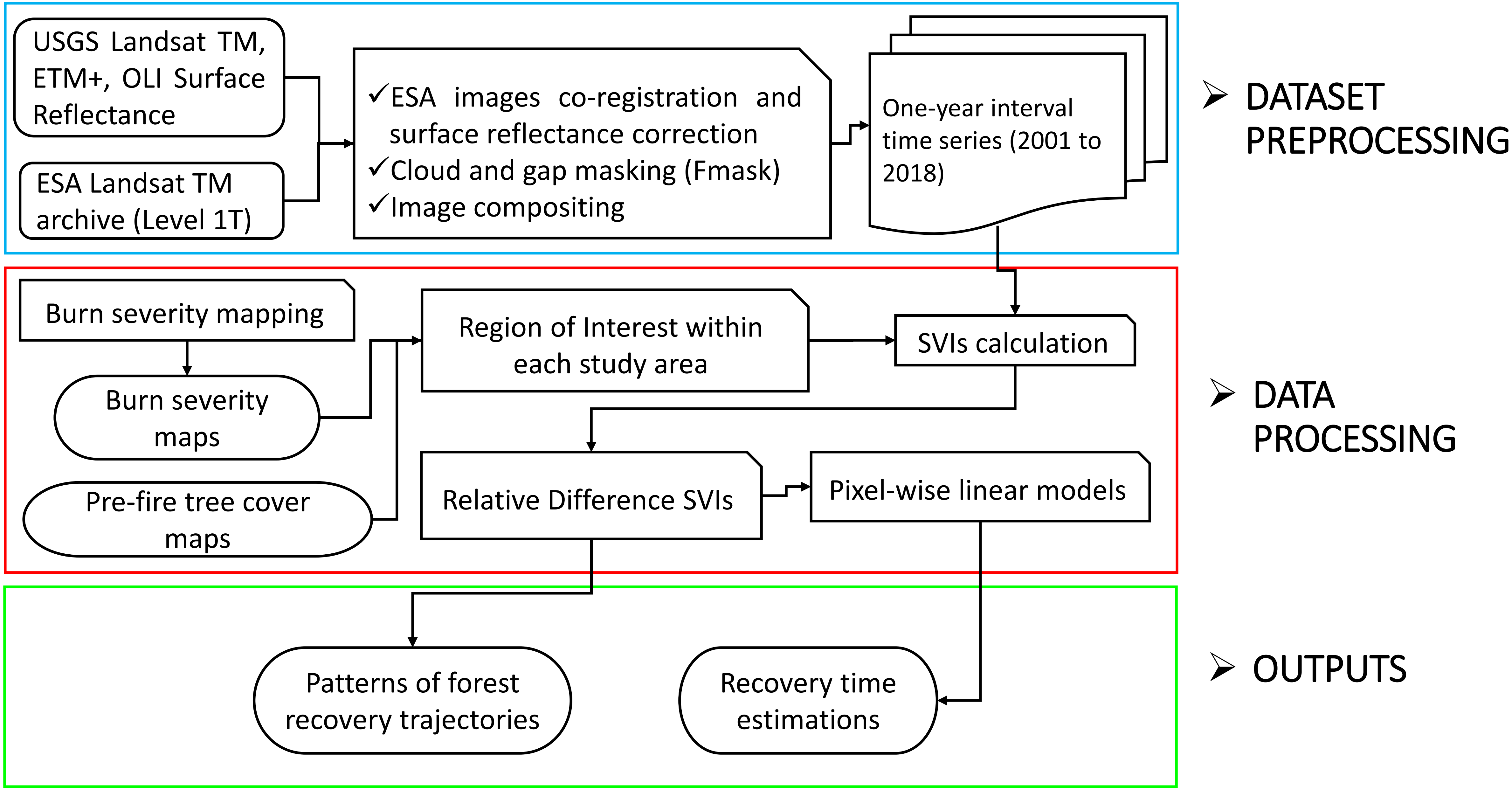


ID	Fire start date	Burned forest (ha)	Forest types
RF (1)	21/07/2007	1860	Conifer plantations (European black pine), pubescent oak, mixed manna ash and European hop-hornbeam
LA (2)	09/08/2007	391	
NA (3)	14/07/2007	1896	
RM (4)	23/07/2007	427	

- Evaluate the ability of different Landsat-derived vegetation indices to detect short to mid-term forest recovery
- Assess post-fire forest recovery dynamics within different forest types and fire severity classes
- Model diachronic forest recovery using spatially explicit linear regression models

CASE STUDY 1

Materials and methods: workflow



CASE STUDY 1

Materials and methods: spectral vegetation indices

- Normalized Difference Vegetation Index (NDVI) = $\left(\frac{\mathrm{NIR} - \mathrm{RED}}{\mathrm{NIR} + \mathrm{RED}}\right)$
- Normalized Difference Moisture Index (NDMI) = $\left(\frac{\mathrm{NIR} - \mathrm{SWIR1}}{\mathrm{NIR} + \mathrm{SWIR1}}\right)$
- Normalized Burn Ratio (NBR) = $\left(\frac{\mathrm{NIR} - \mathrm{SWIR2}}{\mathrm{NIR} + \mathrm{SWIR2}}\right)$
- Normalized Burn Ratio 2 (NBR2) = $\left(\frac{\mathrm{SWIR1} - \mathrm{SWIR2}}{\mathrm{SWIR1} + \mathrm{SWIR2}}\right)$
- Integrated Forest z-score (IFZ) = $\sqrt{\frac{1}{\mathrm{NB}} \sum_{\mathrm{i}=1}^{\mathrm{NB}} \left(\frac{\mathrm{b_{pi}} - \bar{\mathrm{b}}_\mathrm{i}}{(\mathrm{SD})_\mathrm{i}}\right)^2}$
- Forest Recovery Index 2 (FRI2) = $\frac{1}{(\mathrm{IFZ}+1)}$

CASE STUDY 1

Materials and methods: Relative Difference SVI

- ✓ Forest recovery is a gradual process which can be assessed by repeatedly comparing pre and post-fire conditions

- ✓ Relative change detection decreases correlation with pre-fire values when compared to absolute change detection allowing for the comparison between different pre-fire forest canopy densities reflecting different pre-fire ecological conditions (Miller & Thode 2007; Parks *et al*. 2014)

- ✓ SVI offset normalizes phenological and meterological differences between images of consecutive years

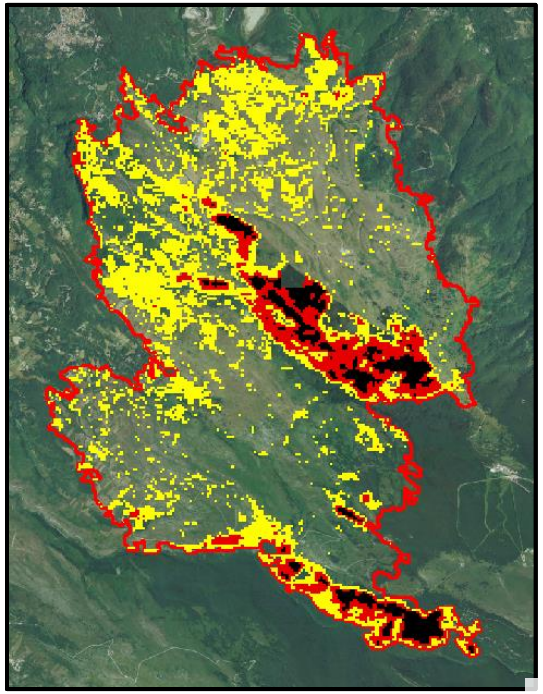
$$\mathbf{RDSVI} = \frac{\left(\left(SVI_{prefire\ median} - SVI_{nth\ postfire\ year}\right) - SVI_{offset}\right)}{SVI_{prefire\ median}}$$

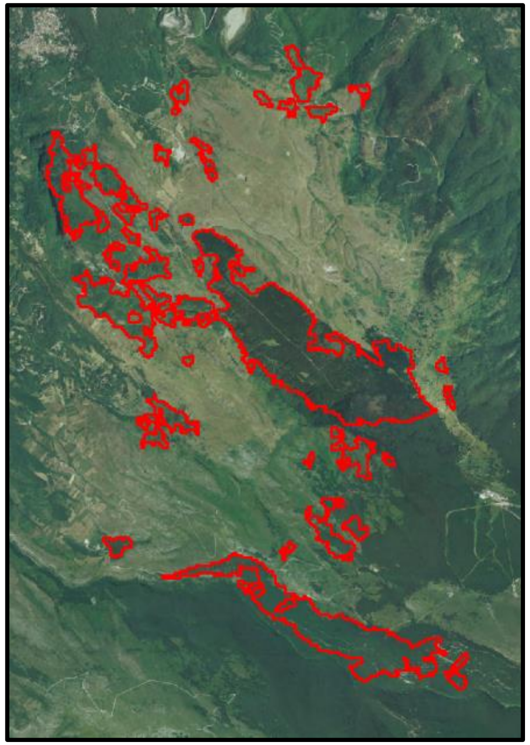
CASE STUDY 1

Materials and methods: mapping disturbed forest

Burned Landsat pixels

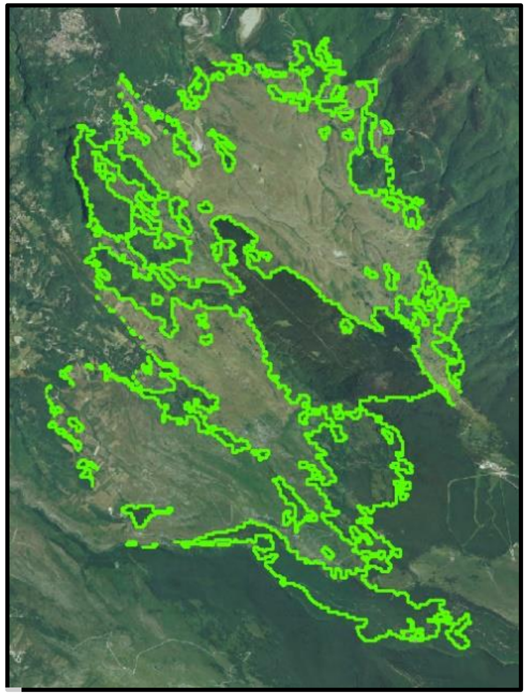
Burn severity map





Pre-fire aerial orthophotos

Prefire Canopy Cover



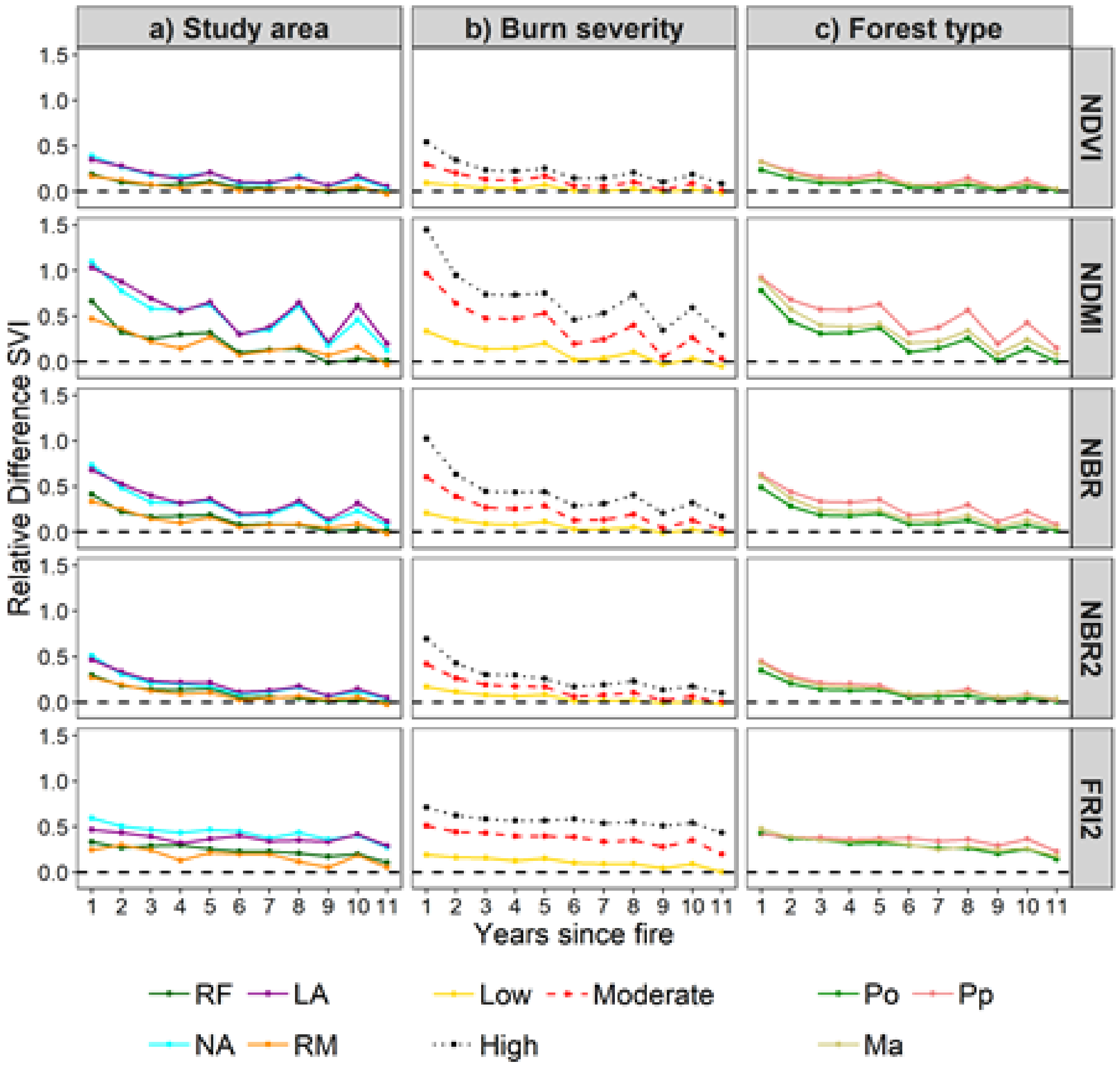
Region of Interest = burned forest

- MMU = 5 Landsat pixels (0,45ha)
- Canopy Cover > 10% (FAO definition of forest)

Materials and methods: modelling forest recovery

- ✓ Forest recovery trajectories explored since 3 years after fire because early post-fire stages are characterized by the colonization of pioneer herbs and shrubs
- ✓ Theil-Sen estimator employed to fit a pixel-wise linear trend in RDSVI time series
- ✓ Non-parametric Mann-Kendall test used to detect significant pixel-wise monotonic trends
- ✓ Pre-withening method reduced serial correlation among consecutive observations to limit type I errors in Mann-Kendall test (Yue and Pilon, 2002)
- ✓ Forecasting recovery time within different forest types and burn severity degrees through inverse linear modelling

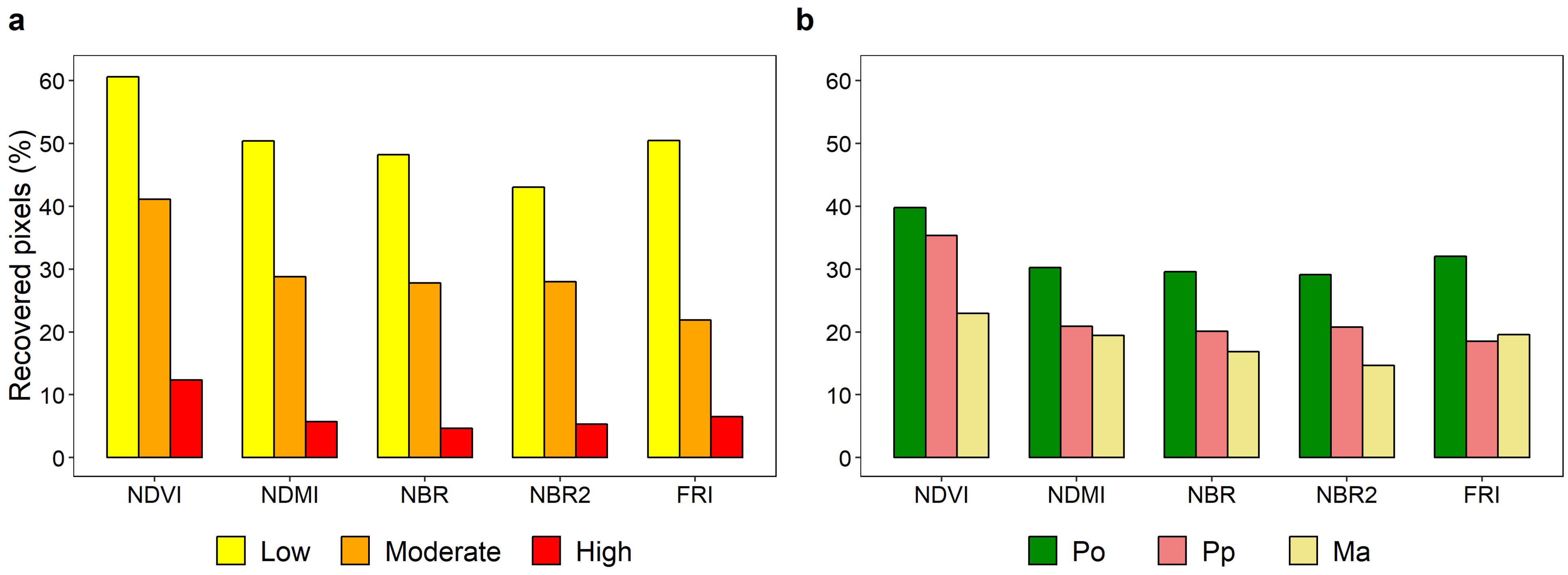
Results: spectral recovery patterns



Main forest types:

- Pubescent oaks (Po)
- Pinus plantations (Pp)
- Manna ash and hop-hornbeams (Ma)

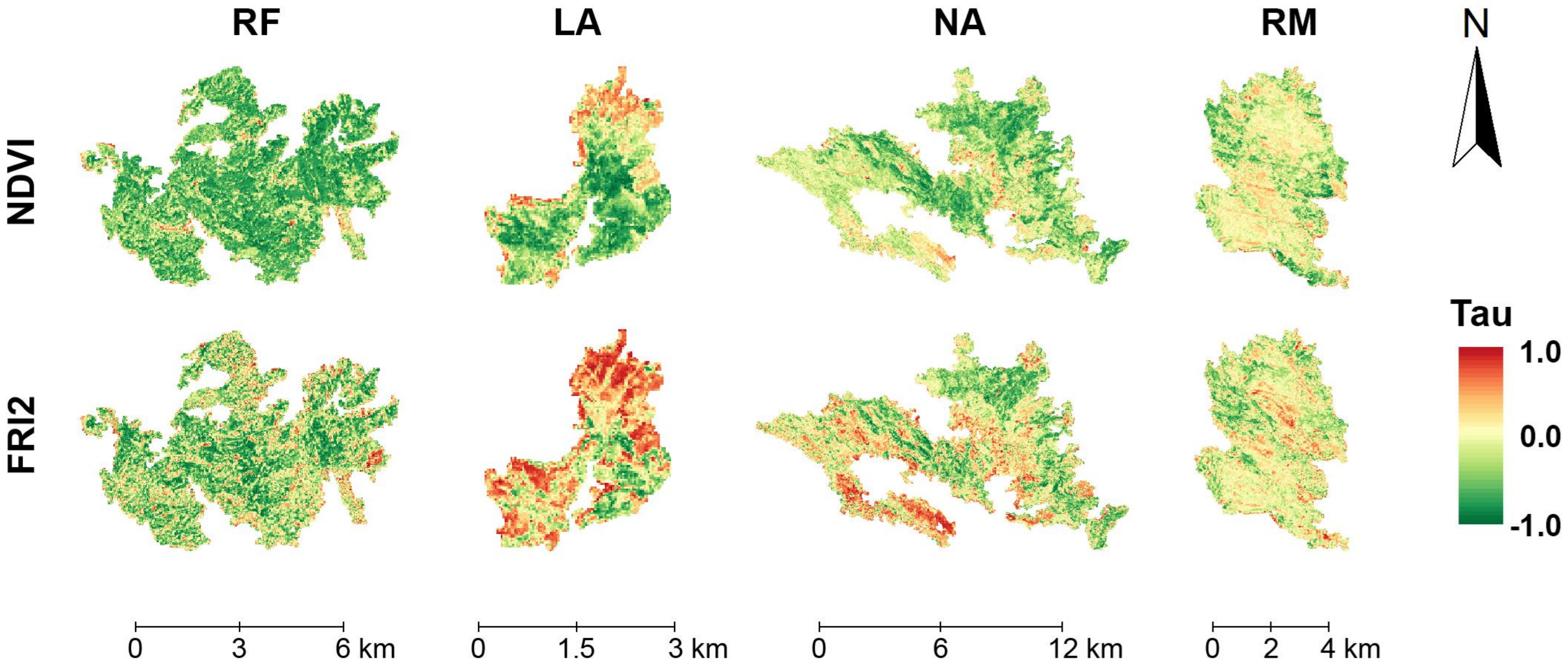
Results: spectral recovery



Forest types:
- Pubescent oaks (Po)
- Pinus plantations (Pp)
- Manna ash and hop-hornbeams (Ma)

Results: modelled forest recovery

- Kendall's Tau (−1 ≤ τ ≤ 1) indicates the strenght of a monotonic trend
- Pixels approaching τ = -1 highlight spectral recovery trends
- Positive values of Tau indicate delayed forest recovery
- Differences between FRI2 and normalized indices trends are clearly distinguishable



Results: modelled forest recovery

- Estimated time (years) required to achieve spectral recovery within different forest types and burn severity classes varies between normalized indices and Forest Recovery Index 2
- Normalized indices take about 10 to 12 years to recover their pre-fire values
- FRI2 highlighted improved sensitivity towards forest biomass (recovery time up to 50% higher) because it depends on the spectral response of mature forest cover

		NDVI	NDMI	NBR	NBR2	FRI2
Burn severity	Low	8.99	8.56	8.85	8.93	**10.13**
	Moderate	9.88	9.70	10.03	9.93	**13.38**
	High	12.02	11.68	11.93	12.20	**18.15**
Forest type	Po	9.74	11.01	10.59	9.98	**12.35**
	Pp	11.1	10.08	10.73	11.12	**15.69**
	Ma	12.18	11.53	11.85	12.36	**15.58**

Conclusions

- Forested ecosystems in the central Apennines are generally highly resilient
- Normalized indices useful to detect short-term vegetation recolonization early after fire occurrence but are suboptimal to assess long-term forest recovery due to low specificity toward the amount of forest cover
- FRI2 is sensitive to the amount of tree canopy cover and biomass (RED and SWIR Landsat bands)
- Modelling forest spectral recovery is useful to plan post-fire management actions and to monitor forest ecosystems at landscape-scale
- Estimating the duration of forest recovery under different conditions is still an open research topic

CASE STUDY 2

Burn severity mapping by integrating remote sensing and field assessment: the big forest fires in Northwestern Italy during autumn 2017

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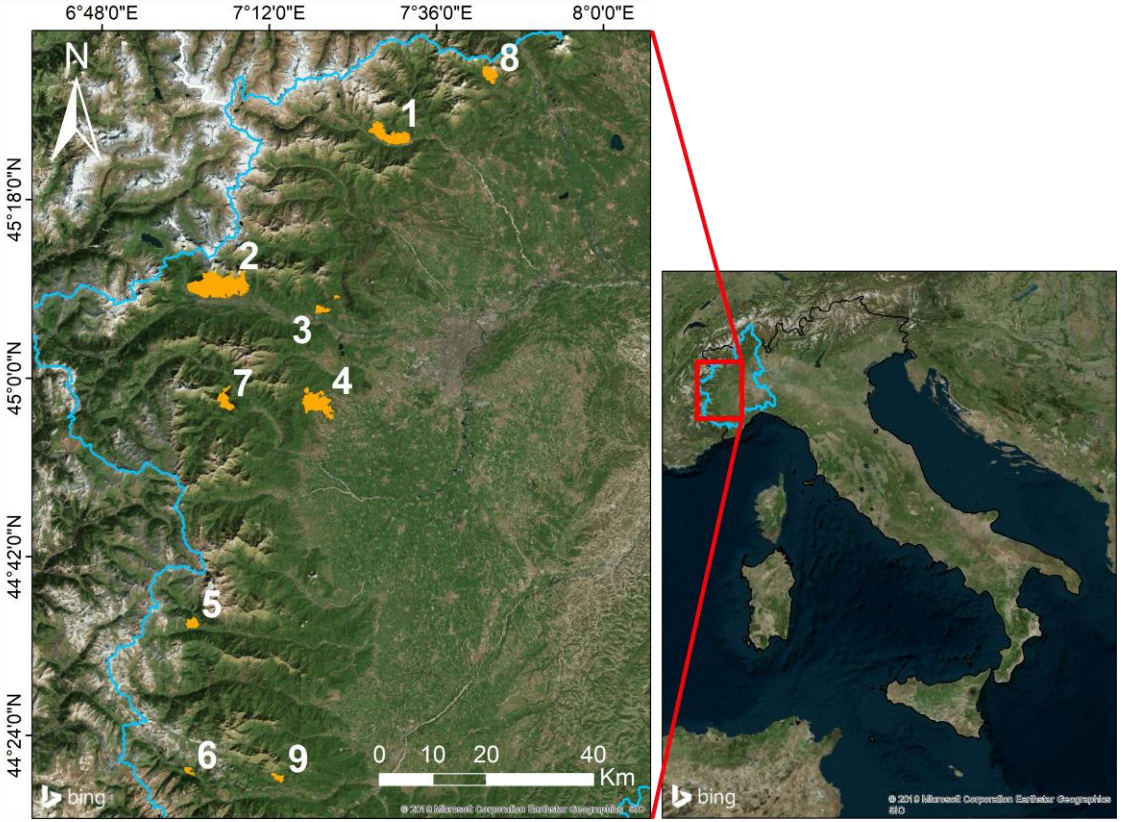
Università degli studi di Torino

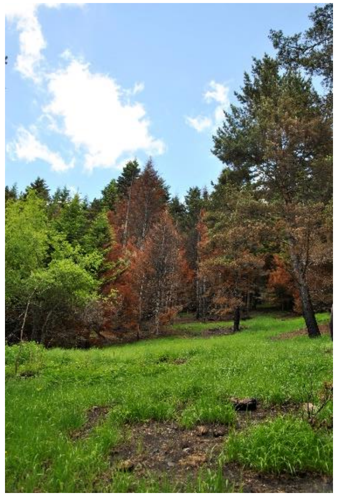
Study areas



- Nine big wildfires occurred during autumn 2017 in Piedmont (NW Italy) following a severe drought
- Total burned area was 10.000 ha, ranging from 164 ha to 3.974 ha
- Affected forests included mainly broadleaved species (European Chestnut, Beech, Downy Oak), but conifer stands (European Larch, Scots Pine and Silver Fir) were the most severely affected

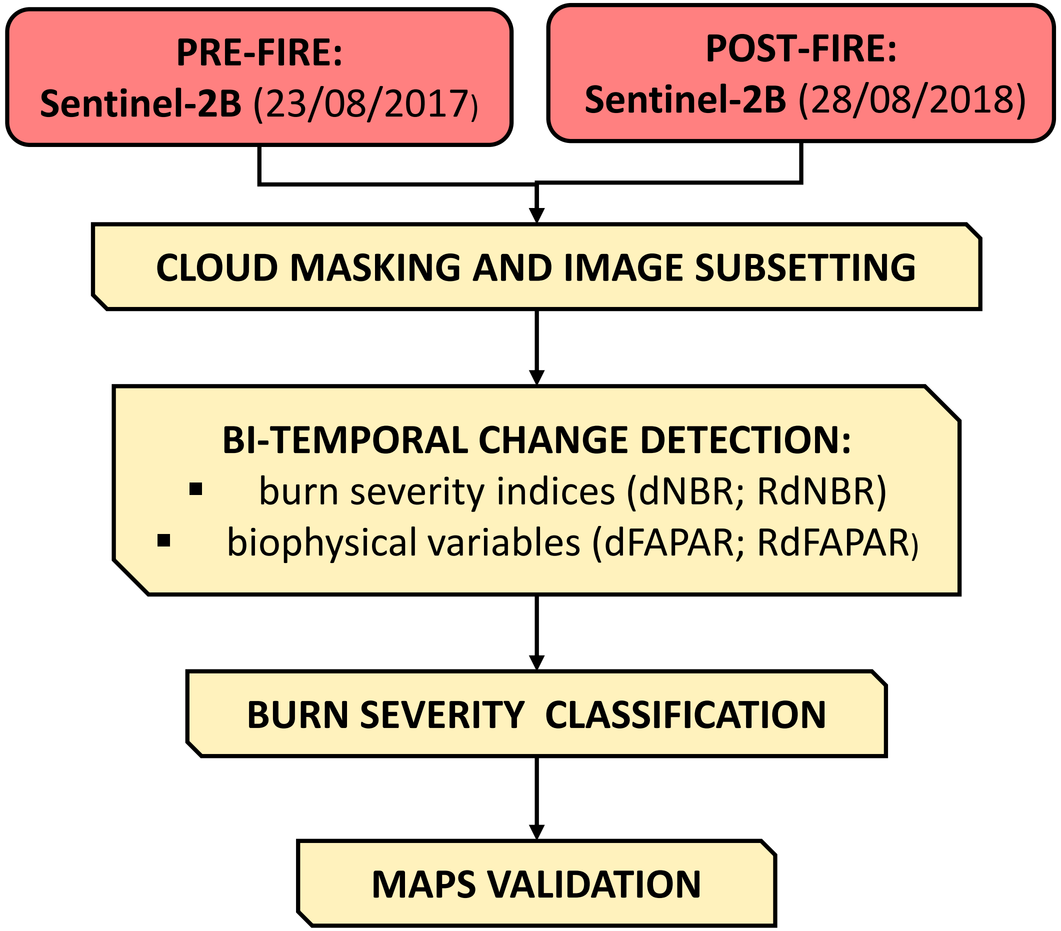
Objectives

- Mapping burn severity of each fire by integrating multispectral satellite data and field protocols for burn severity assessment
- Support the development of a post-fire management plan aimed to define priority areas and intervention techniques




Materials and methods: burn severity mapping workflow

- Sentinel-2 B8A (NIR Narrow) and B12 (SWIR2) used to compute Normalized Burn Ratio (NBR)
- Delta NBR (dNBR) and Relative differenced NBR (RdNBR) employed to assess burn severity
- Biophysical variables computed using the Biophysical Processor available in the Sentinel Application Platform (SNAP)
- Relative change detection algorithm applied to the biophysical variables: $(BioVar_{pre} - BioVar_{post}) * 1000 / BioVar_{pre}$
- *Fraction of Absorbed Photosynthetically Active Radiation* (FAPAR) selected among biophysical variables



Materials and methods: field assessment

- Composite Burn Index (CBI) field protocol to assess burn severity within circular plots (20m diameter) and validate satellite-inferred burn severity maps

- Field surveys carried out between June and September 2018 in all of the nine fires

- CBI plots located within homogeneous severity patches using fire severity maps produced with Sentinel-2 images acquired soon after the end of the fires (October/November 2017)

- All plots used aggregated to perform the analyses because of the similarity between fires

Low Burn Severity

Moderate Burn Severity

High Burn Severity

Materials and methods: field assessment

CBI (**Composite Burn Index**) from FIREMON (Fire Effects Monitoring and Inventory System), developed by the USDA Forest Service

- Represents the magnitude of fire effects combined across all strata
- Useful for correlation with remote sensing data
- CBI scoring (0 – 3) is completed for each of the 5 strata and averaged to the desired composite level

A. Total plot

B. Understory

1. Substrates
2. Herbs, low shrubs and trees less than 1 m
3. Tall shrubs and trees 1 to 5 m

C. Overstory

4. Intermediate trees (pole-sized trees, subcanopy)
5. Big trees (upper canopy, dominant/co-dominant trees)

PROTOCOLLO DI RILIEVO DELLA SEVERITA'				
DATA(gg/mm/aaaa): / /	INCENDIO #	SITO:	PLOT #	CLASSE SEVERITA':
RILEVATORI:				CAT. FORESTALE:
COORDINATE CENTROIDE PLOT:				
% SUPERFICIE PLOT BRUCIATA:	Ø PLOT SOTTOBOSCO (A, B, C) / Ø PLOT PIANO ARBOREO (D, E): /			
NOTE:				

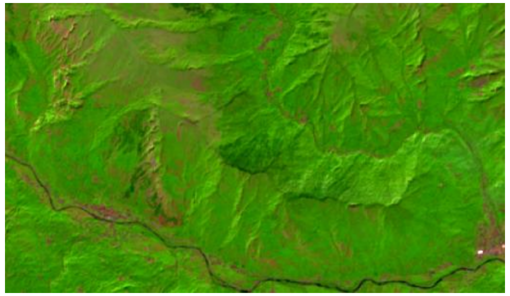
STRATI	SCALA DELLA SEVERITA'							PUNTEGGIO
	Non bruciato	Bassa		Media		Elevata		
	0	0,5	1	1,5	2	2,5	3	
A. LETTIERA E ORIZZONTI ORGANICI						**FCOV PRE/POST=**	/	
% Copertura pre: Lettiera=	**O. organici=**		**Suolo/roccia=**					
Lettiera/Combustibili fini (Ø <7,6 cm)	Inalterato	--	50% della lettiera	--	100% della lettiera	>80% combustibili fini	98% combustibili fini	
Orizzonti organici	Inalterati	--	Poco consumati	--	50% di perdita; bruciati in profondità	--	Totalmente consumati	
Combustibili medi (Ø >7,6 cm e <20,3 cm)	Inalterati	--	20% consumati	--	40% consumati	--	>60% consumati; bruciati in profondità	
Combustibili pesanti (Ø >20,3 cm)	Inalterati	--	10% consumati	--	25% consumati, bruciati in profondità	--	>40% consumati; bruciati in profondità	
Cambiamento nella copertura di suolo e roccia nuda	Inalterato	--	10% di cambiamento	--	40% di cambiamento	--	>80% di cambiamento	
			A ∑=		**N=**	**$\bar{X}$=**		
B. ERBE, ARBUSTI BASSI E ALBERI <1 METRO						**FCOV PRE/POST=**	/	
% Fogliame alterato (nero-marrone) (Considerare solo specie legnose)	Inalterato	--	30%	--	80%	95%	100% + perdita rami	
Frequenza % Sopravvissuti	100%	--	90%	--	50%	<20%	Nessuno	
Rinnovazione gamica (autoctona e alloctona) e rinnovazione agamica da polloni radicali	Inalterata	--	Scarsa	--	Mediamente abbondante	Abbondante - Scarsa	Da scarsa ad assente	
Nuovi polloni da ceppaia (rinnovazione agamica)	Abbondanti	--	Da abbondanti a medi	--	Mediamente numerosi	--	Da pochi a nessuno	
Composizione specifica - Abbondanza rel.	Inalterata	--	Poco cambiata	--	Medimente cambiata	--	Molto cambiata	
			B ∑=		**N=**	**$\bar{X}$=**		
C. ARBUSTI ALTI E ALBERI TRA 1 E 5 METRI						**FCOV PRE/POST=**	/	
% Fogliame alterato (nero-marrone)	0%	--	20%	--	60-90%	>95%	Notevole perdita di rami	
Frequenza % Sopravvissuti	100%	--	90%	--	30%	<15%	<1%	
% Cambiamento di copertura	Inalterata	--	15%	--	70%	90%	100%	
Composizione specifica - Abbondanza rel.	Inalterata	--	Poco cambiata	--	Medimente cambiata	--	Molto cambiata	
			C ∑=		**N=**	**$\bar{X}$=**		
D. ALBERI DEL PIANO DOMINATO						**FCOV PRE/POST=**	/	
Pre incendio: % Individui vivi=		**% Individui morti =**						
% Verde (inalterato)	100%	--	80%	--	40%	<10%	Assente	
% Nero (bruciato)	Assente	--	5-20%	--	60%	>85%	100% + perdita di rami	
% Marrone (foglie scottate, rami morti)	Assente		5-20%		40-80%	<40% o >80%	Assente perché bruciato	
Frequenza % Sopravvissuti	100%	--	90%	--	30%	<15%	<1%	
% Mortalità della chioma	Inalterato	--	15%	--	60%	80%	100%	
Altezza di scottatura del tronco	Assente	--	1,5 m	--	2,8 m	--	>5 m	
Post incendio: % Individui morti per bruciatura base del tronco=				**% Individui schiantati=**			**% Individui morti=**	
			D ∑=		**N=**	**$\bar{X}$=**		
E. ALBERI DEL PIANO DOMINANTE E ALBERI CODOMINANTI						**FCOV PRE/POST=**	/	
Pre incendio: % Individui vivi=		**% Individui morti =**						
% Verde (inalterato)	100%	--	95%	--	50%	<10%	Assente	
% Nero (bruciato)	Assente	--	5-20%	--	60%	>85%	100% + perdita di rami	
% Marrone (foglie scottate, rami morti)	Assente		5-20%		40-80%	<40% o >80%	Nero (Bruciato)	
Frequenza % Sopravvissuti	100%	--	90%	--	30%	<15%	<1%	
% Mortalità della chioma	Inalterato	--	10%	--	50%	70%	100%	
Altezza di scottatura del tronco	Assente	--	1,8 m	--	4 m	--	>7 m	
Post incendio: % Individui morti per bruciatura base del tronco=				**% Individui schiantati=**			**% Individui morti=**	
			E ∑=		**N=**	**$\bar{X}$=**		

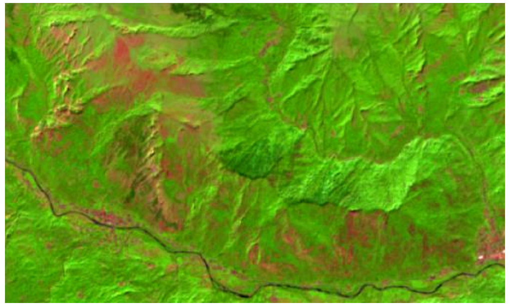
Materials and methods: remote sensing and field data

Pre-fire (August 2017)

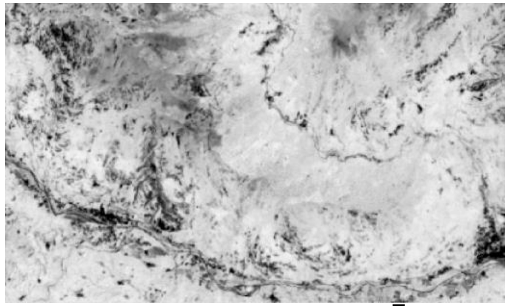
Post-fire (August 2018)

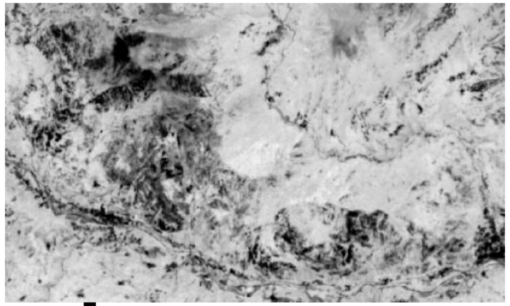
Sentinel-2



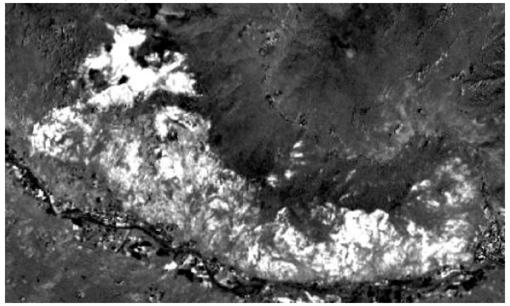


NBR

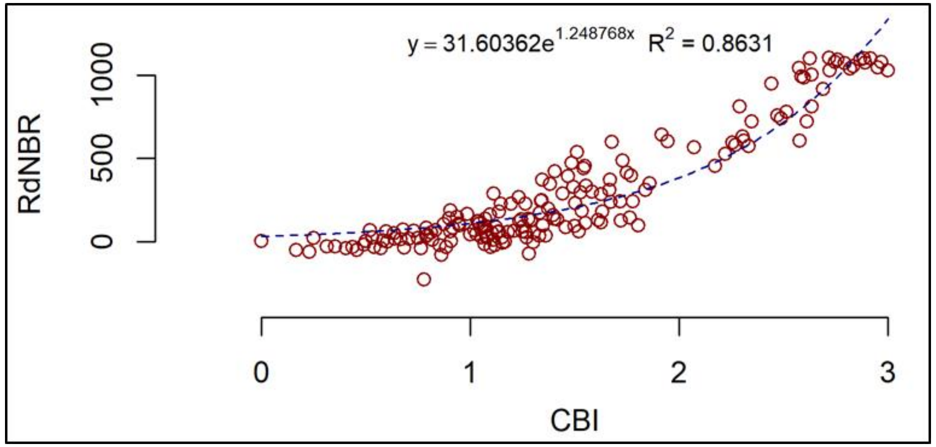




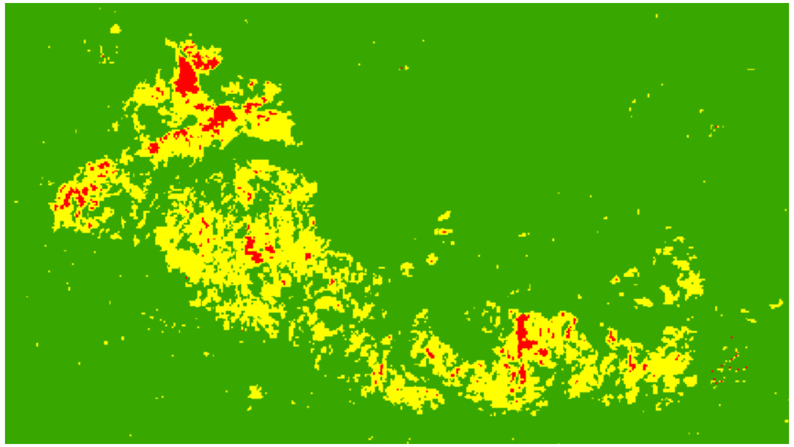
RdNBR



CBI – RdNBR model

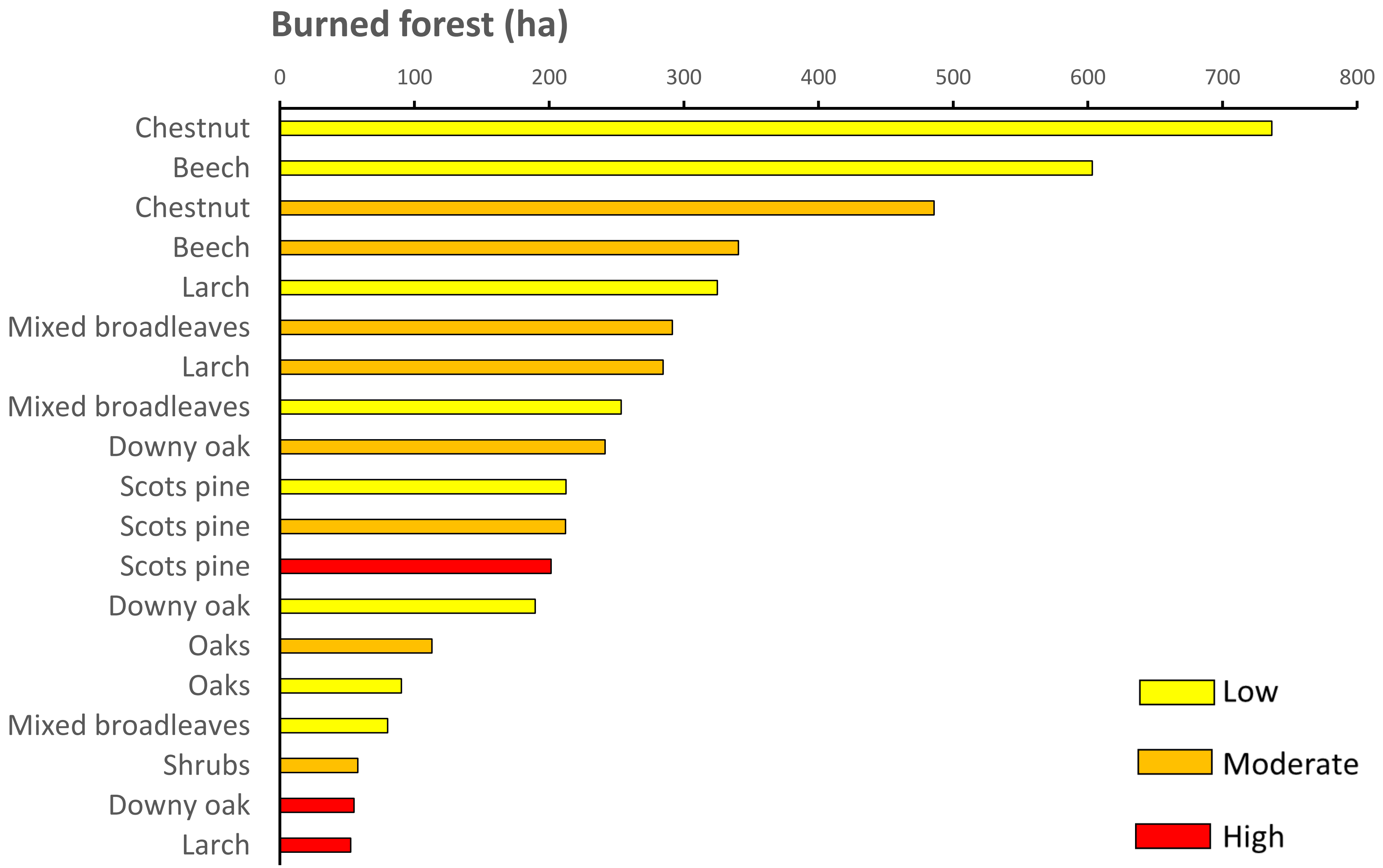


Burn severity map



CASE STUDY 2

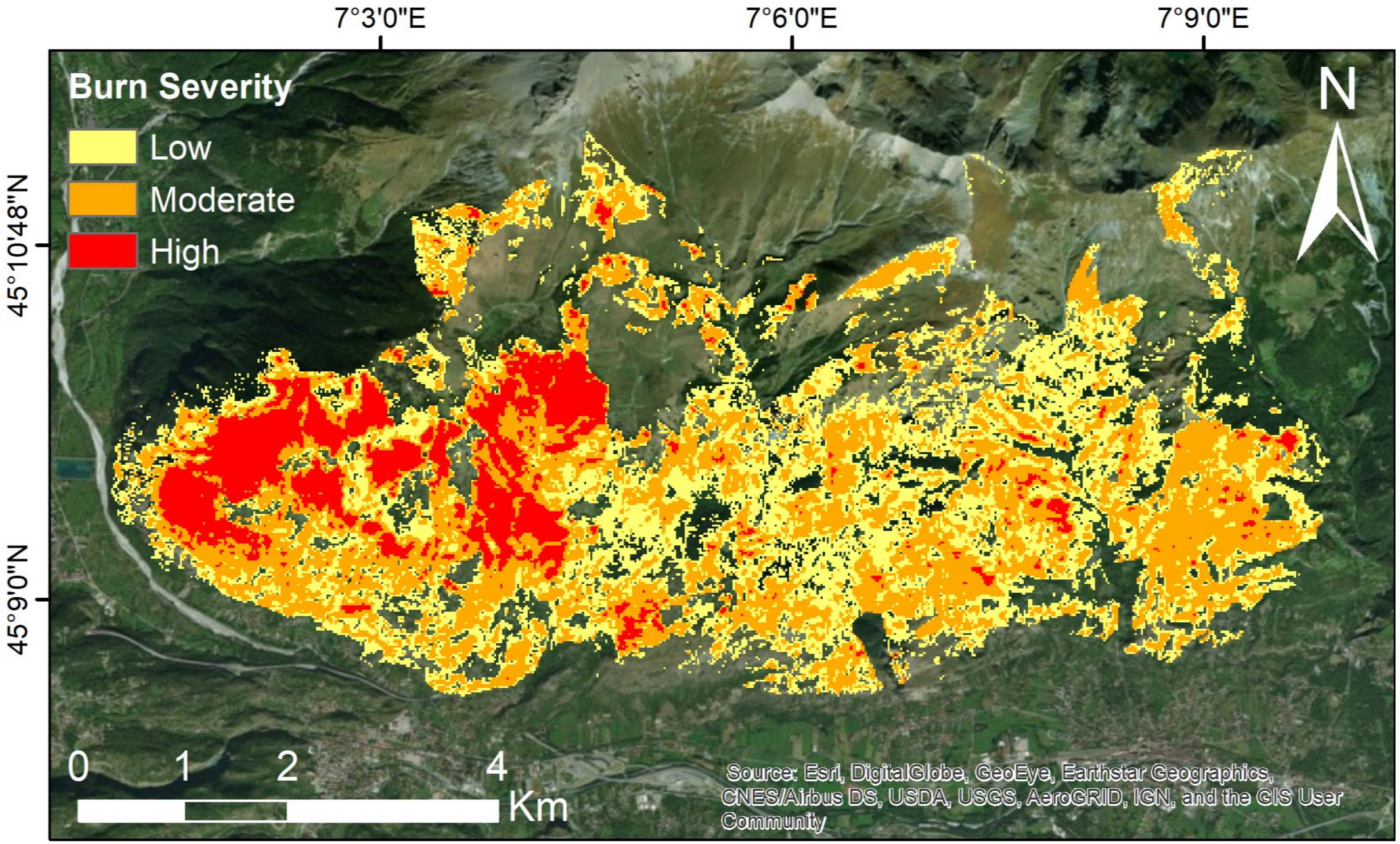
Results: burn severity mapping

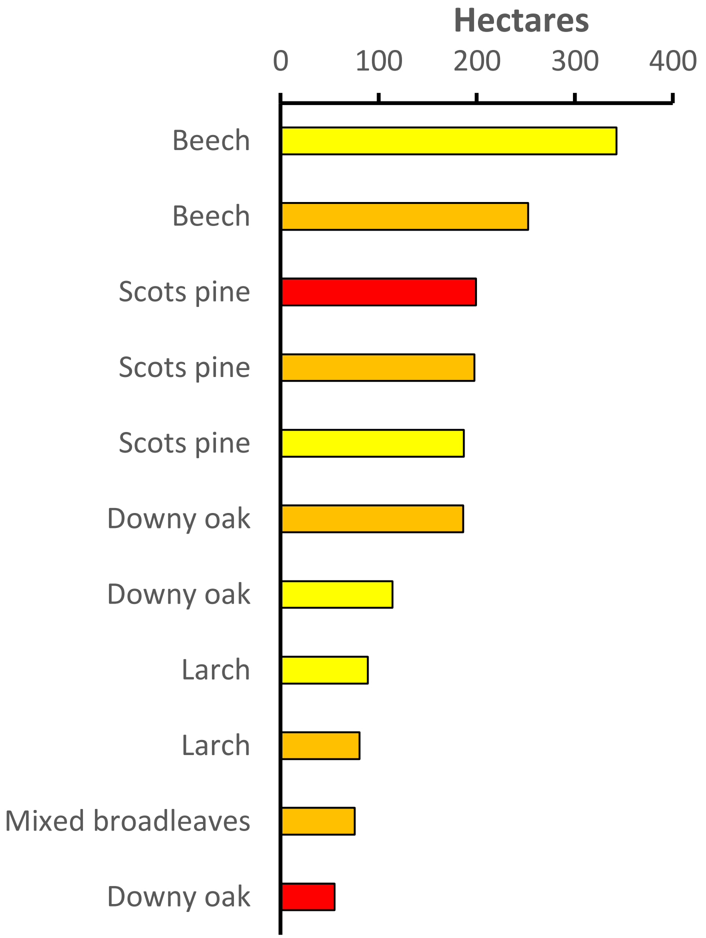


CASE STUDY 2

Results: burn severity mapping

Susa fire: total burned area 3.974 ha, burned forest 2.609 ha





CASE STUDY 2

Results: burn severity mapping accuracy

(%)	**dNBR**	**RdNBR**	**dFAPAR**	**RdFAPAR**
Overall accuracy	63,75	**65,74**	58,57	63,35
UA Unburned	97,70	97,7	88,60	88,6
UA Low	47,70	50	44,30	48,9
UA Moderate	50,60	50,6	45,80	50,6
UA High	91,70	**100**	86,10	97,2
PA Unburned	54,40	54,4	52,70	55,7
PA Low	60,90	62	62,90	61,4
PA Moderate	67,70	73,7	57,60	64,6
PA High	80,50	**81,8**	63,30	76,1
Kappa statistic	0,51	0,54	0,45	0,50

Conclusions

- Good overall accuracy of burn severity maps inferred from multispectral satellite data considering the moderate and the high burn severity classes
- The classification was accurate enough for the aims of post-fire management which is focused on interventions within high severity patches
- Burn severity metrics obtained using NBR index produced more accurate results when compared to FAPAR obtained using the Biophysical Processor in the Sentinel-2 Toolbox
- Further research is needed to understand how biophysical variables can be used to effectively estimate changes caused by fire on forest ecosystems

CASE STUDY 3

Exploring fire-related dynamics in coniferous forests dominated by Scots pine (*Pinus sylvestris*) using Landsat time series and field data in the Aosta Valley (Italy)

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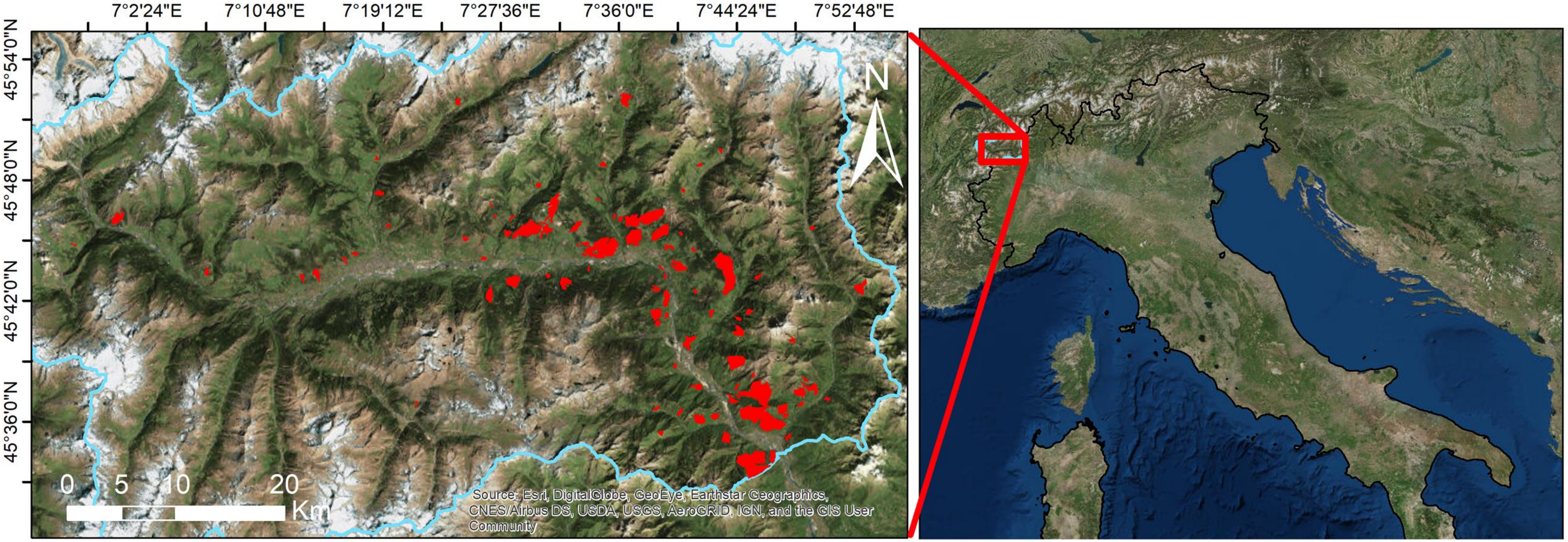
TESAF

CASE STUDY 3

Study area



- Wildfires in the Aosta Valley mostly occur in south-facing slopes where xeric conditions favor the presence of highly flammable conifer stands dominated by Scots pine (*Pinus sylvestris*)
- Although stand-replacing wildfires affected about 20% of the total burned forest surface from 1989 to 2017, the scarce fire adaptations of Scots pine poses serious problems for its regeneration

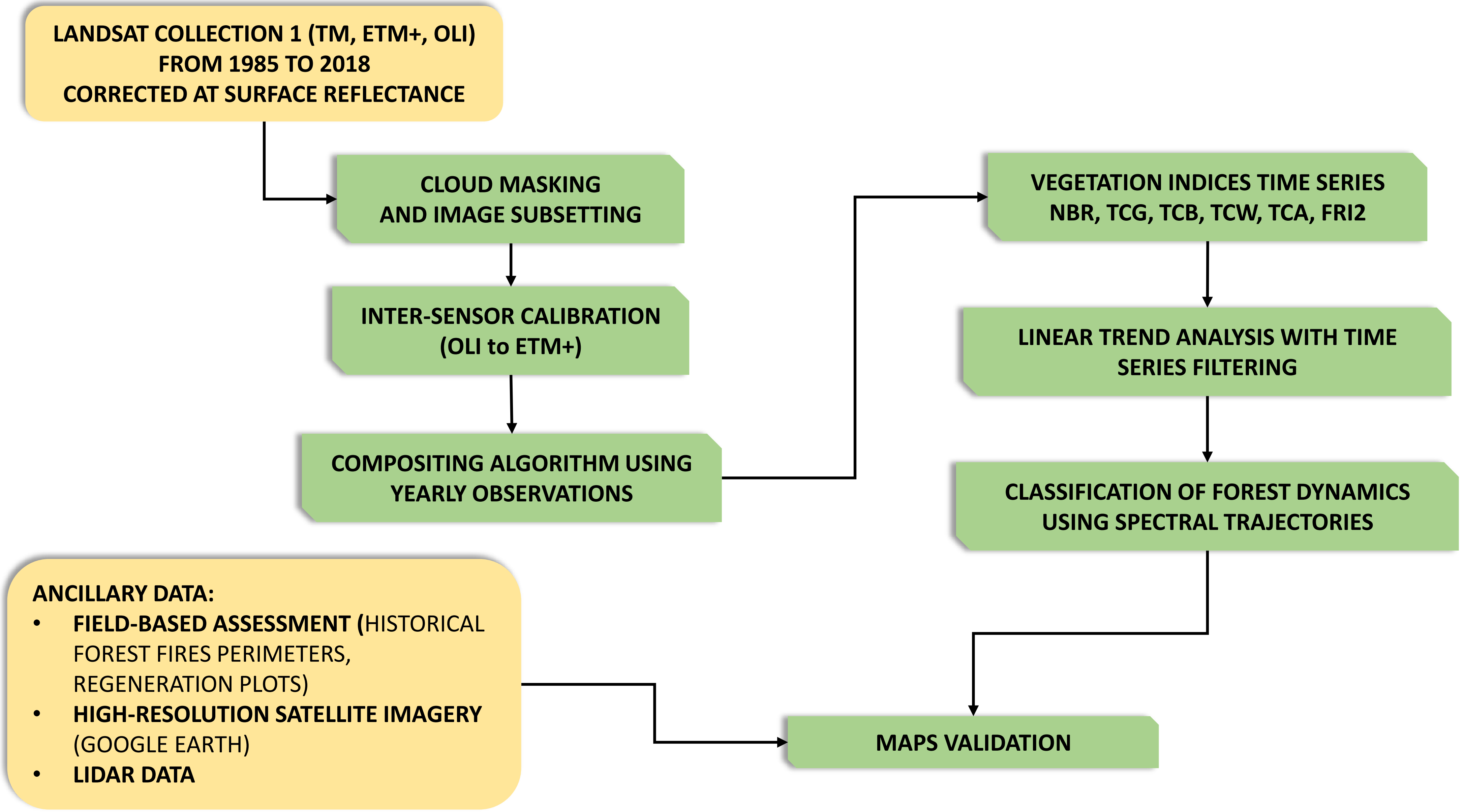
Research objectives

- Detect fire-related dynamics through Landsat time series analysis and an automated mapping approach
- Investigate regeneration dynamics of tree specie with low fire adaptations (Scots pine) with remote sensing (under development)
- Evaluate the long-term effectiveness of post-fire management strategies to enhance forest recovery (under development)

Crown fire in Nus/Verrayes (AO) occurred in March 2005. Burned forest was dominated by *Pinus sylvestris* (160 ha). Photo credit G. Cesti.

Fieldwork in the Bourra fire (2005) for sampling forest regeneration in a *Pinus sylvestris* stand.

Materials and methods



Materials and methods

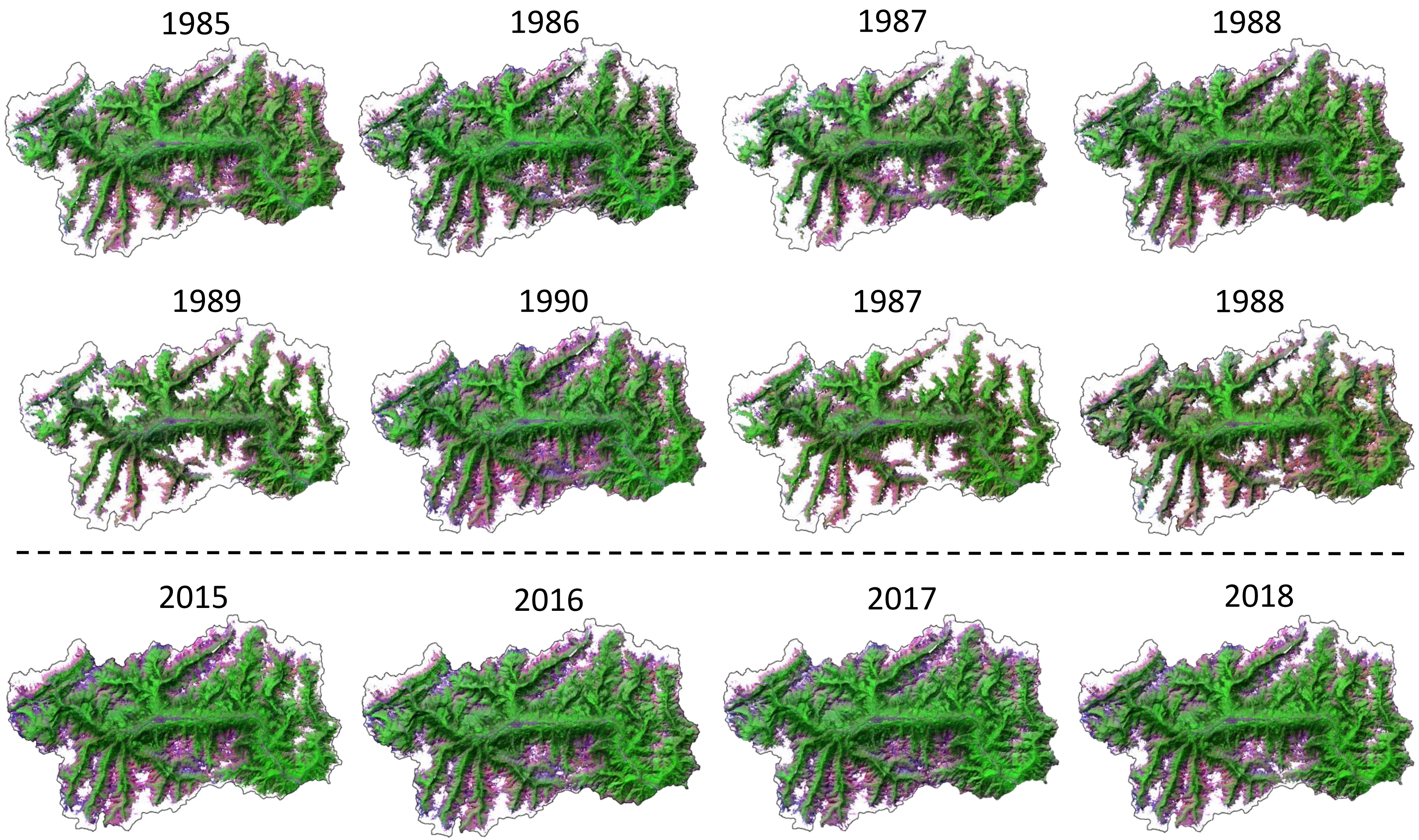
- 405 Landsat Collection 1 images acquired by TM, ETM+ and OLI sensors corrected at surface reflectance using the LEDAPS and LaSRC algorithms through the ESPA on-demand interface provided by the USGS

- All acquisitions with less than 80% cloud cover from the begin of June to the end of September used to create a one-year composite image through a pixel-level compositing algorithm (geometric median)

- Changes of vegetation indices trends detected using linear trend filtering techniques based on moving windows

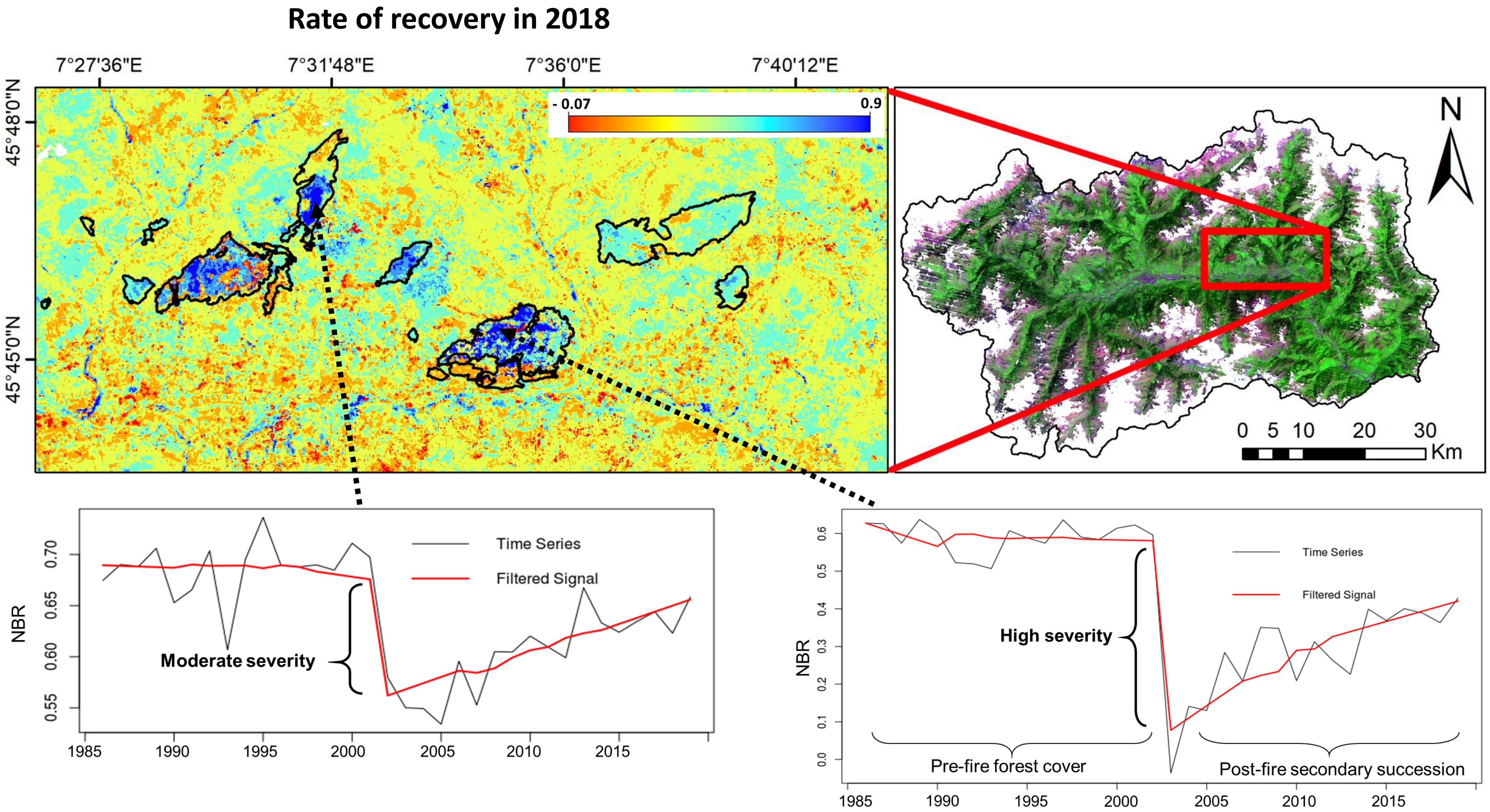
- Regenerating stands were mapped by classifying the (positive) slope of the spectral trends. This approach can be used to distinguish between forest regeneration among forest dynamics in the short to the medium term

Materials and methods



CASE STUDY 3

Results: recovery maps



CASE STUDY 3

Results: time series analysis

- Interpolation algorithms needed to fill data gaps of some Landsat pixel time series if only scenes from the same year were used to generate composites
- Non-parametric trend filtering based on moving windows able to detect both abrupt and gradual trend changes
- Pixels affected by moderate-low to high burn severity successfully detected within the time window
- Depending when fire occurred, gaps detected either in the same year when the fire occurred or in the following year
- Trend slope classification showed good results in discriminating between dynamics of regenerating and undisturbed stands

Considerations and future work

- The methodology is still under development but it’s suitable to detect any type of forest disturbance and the subsequent forest dynamics

- Validation of disturbance and recovery maps will be performed using field assessment of forest regeneration and remote sensing data (high-resolution imagery, LiDAR data)

- Post-fire interventions on future fires could be driven by results obtained from forest recovery dynamics inferred from Landsat time series

Thank you for your attention