THESIS PROPOSAL

1. Title

Multiscale remote sensing of intertidal vegetation of European coasts in response to natural and anthropogenic pressures

Key-words: angiosperms, anthropogenic pressures, multi-sensor analysis, macroalgae, microphytobenthos, interannual variations, intertidal zones, seasonality

2. Laboratory & Research team

Laboratoire Mer Molécules Santé EA2160

The Mer Molécules Santé (MMS) laboratory at the University of Nantes is a member of the Institut Mer & Littoral (IUML - FR CNRS 3473). This laboratory has 130 researchers (75 permanent) located at different universities in the Pays de la Loire region (http://www.mms.univ-nantes.fr/). Within MMS, the Remote Sensing & Benthic Ecology (RSBE) team works on multi- and hyperspectral remote sensing of coastal areas at different observation scales. Research activities concern the study of the structure and functioning of ecosystems at macro-scale, but also the analysis of micro-scale processes (a few centimeters) apprehended using field imaging spectrometers, airborne, or laboratory. The analysis of the time series of multispectral satellite missions at high (10 - 20 m with SPOT and Sentinel-2) and medium (300 m with MERIS and Sentinel-3) spatial resolution makes it possible to acquire additional data of high spectral resolution and spatial (1 m) of airborne hyperspectral missions. The RSBE team studies the primary and secondary production of coastal areas within the framework of projects related to aquaculture (ANR-GIGASSAT and H2020 TAPAS projects), sets up campaigns at sea to measure the optical properties of the seawater (INSU TURBO and CNES LASHA projects) and has been involved in European and national projects via high spatial resolution remote sensing programs : Pléiades User Group (PUG), SPOT4 Take5 (en collaboration avec le GIPLE), MyGIC-SPOT6 and Venμs.

Remote Sensing & Benthic Ecology (RSBE)
https://mms.univ-nantes.fr/fr/rsbe-remote-sensing-benthic-ecology

3. Supervision

Supervisor : Laurent Barillé – Pr
Co-supervisor : Pierre Gernez – MC

https://www.univ-nantes.fr/laurent-barille
https://www.univ-nantes.fr/pierre-gernez

The supervision is made up of two researchers from the RSBE team at the MMS Laboratory of the University of Nantes, Pierre Gernez (MC) and Laurent Barillé (Pr). The RSBE team has been studying intertidal zones for twenty years using multi- and hyperspectral remote sensing, in particular through collaboration with the Laboratory of Planetology and Geodynamics of the University of Nantes, which own Hyspex hyperspectral cameras and carries out airborne campaigns. The RSBE team has published work on most habitats of intertidal ecosystems, in

particular microphytobenthos, seagrass beds, wild oyster reefs, in journals such as *Remote Sensing of Environment* or *Remote Sensing*. Five PhD were defended on these subjects. More recently, we have been interested in machine-learning methods, which we wish to implement to map habitats on a national and European scale. We are currently involved in the European H2020 CoastObs project (https://coastobs.eu/) which relies on the use of high spatial and temporal resolution satellite imagery to map coastal environments.

4. Contact informations

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5. General context, objectives, general interest, plan

Intertidal habitats by marine plants can be observed at low tide (angiosperm meadows, microphytobenthos, macroalgae) and are strongly impacted by human activities: seagrass meadows are threatened by numerous human activities (McKenzie et al., 2020), microphytobenthos is affected by the global decrease in intertidal mudflats (Murray et al., 2019), the areas colonized by macroalgae could be reduced by the expansion of wild oysters (Le Bris et al., 2016). These habitats fulfill recognized ecological functions: protection against coastal erosion, mitigation of the effects of eutrophication, fixation of atmospheric CO_2, biodiversity hotspots sheltering specific flora and fauna. Intertidal areas are nevertheless difficult to access, especially mudflat areas, and traditional field sampling would require too much time and effort to repeatedly observe all of the areas considered. However, the regulatory demand for monitoring the good ecological status of coastal marine habitats requires regular mapping. This is the case of the Water Framework Directive (WFD) or the Marine Strategy Framework Directive (MSFD) which use the diversity of marine habitats as a bioindicator of the quality of coastal or estuarine waters (Borja et al. 2013; Zoffoli et al. submitted). Remote sensing is an innovative tool for retrieving the Essential Biodiversity Variables from these habitats (EBV *sensu* Peirera et al. 2013; Skidmore et al. 2015), but past and present satellite missions do not have the optimal technical characteristics (spatial resolution, spectral and temporal) to be fully operational (Muller-Karger et al., 2018).

For some habitats, multispectral resolution may be sufficient under certain conditions (Zoffoli et al. 2020), but risks of confusion remain. For others, greater spectral resolution is essential in order to distinguish taxonomically distinct classes of organisms (Fyfe et al. 2003; Launeau et al. 2018, Méléder et al. 2018). The principle of identification is in fact based in part on the presence of absorption bands in the visible linked to the presence of photosynthetic and accessory pigments, which can be detected and quantified by high performance liquid chromatography (Méléder et al. 2003, 2005; Bargain et al. 2013; Jesus et al. 2014). Analysis of the phenology of these organisms could also be exploited to aid in their discrimination. Thanks to its revisit time of 2 to 5 days, the Sentinel 2 satellite can also identify seasonal cycles of marine plants (Zoffoli et al. 2020).

Temporal variations of intertidal vegetation have been much less documented than spatial variations, in particular due to the reduced availability of high spatial resolution satellite images (*eg.* SPOT, LANDSAT) and the constraints associated with acquiring images at low tide. Even since the launch of Sentinel 2 in 2015, there is currently no sensor having both high spatial / spectral and temporal resolutions (Figure 1). This thesis will therefore be based on a multi-sensor analysis (MSI / Sentinel 2; OLCI / Sentinel 3; Terra / MODIS) and use very-high spatial resolution mapping by drone.

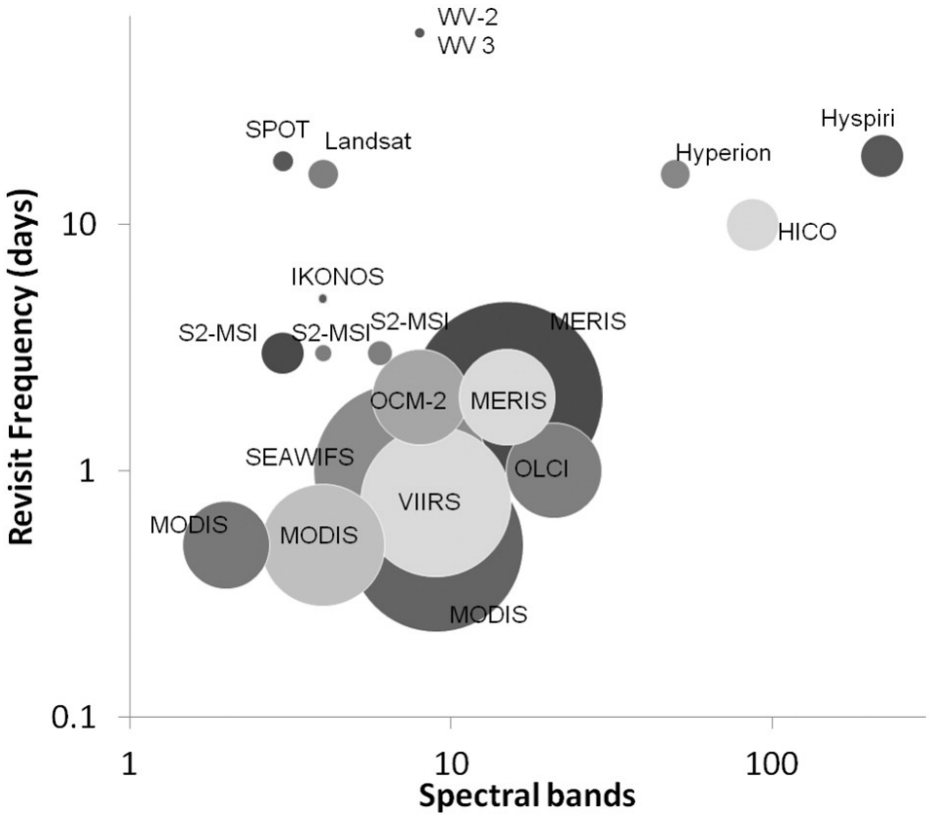

Fig. 1. Crossing of the spectral (x-axis), temporal (y-axis) and spatial (size of circles) characteristics of the main satellite sensors used to observe coastal areas. Hyperspectral sensors (Hyperion, HICO, Hyspiri) have a hundred spectral bands but have a low revisit frequency and insufficient spatial resolution. Sensors with the shortest revisit time (MODIS, VIIRS, OLCI) have lower spectral resolution (between 2 - 20 spectral bands) and low spatial resolution (250 m - 1 km) (Hestir et al. 2015). With ten spectral bands, a resolution of 10 m, and a revisit time of <5 days, Sentinel 2 (S2-MSI) offers an interesting compromise.

This thesis will focus on the three main primary producers of intertidal zones of muddy and sandy substrate: seagrass beds of marine angiosperms, macroalgae and microphytobenthos (Fig. 2). Schorre plants will not be considered. The progress of the thesis is planned gradually with a progression from the micro-scale (centimetric resolution) allowing to approach processes from stationary observations of a given habitat, then at mesoscale (decametric resolution) in a coastal zone with time series covering 2 to 4 decades, and finally the macro-scale (kilometric influence) for several sites on the French and European coasts.

Objectives are linked to the mapping of spatio-temporal variations of biodiversity variables that can be retrieved from plants in intertidal zones based on Earth Observations. With its high frequency of observations and high spatial resolution Sentinel 2 data will be used to analyse the main natural and anthropogenic factors responsible for the changes (in terms of diversity, spatial distribution, and temporal dynamics). Finally, the challenge will be to show that remote sensing can meet the regulatory demand for monitoring the ecological state of habitats of community interest (Papathanasopoulou et al. 2019) and that microphytobenthos could be used as an indicator of the quality of water bodies, in the same way as marine angiosperms and macroalgae (Ribeiro et al. 2018; Oiry & Barillé 2021).

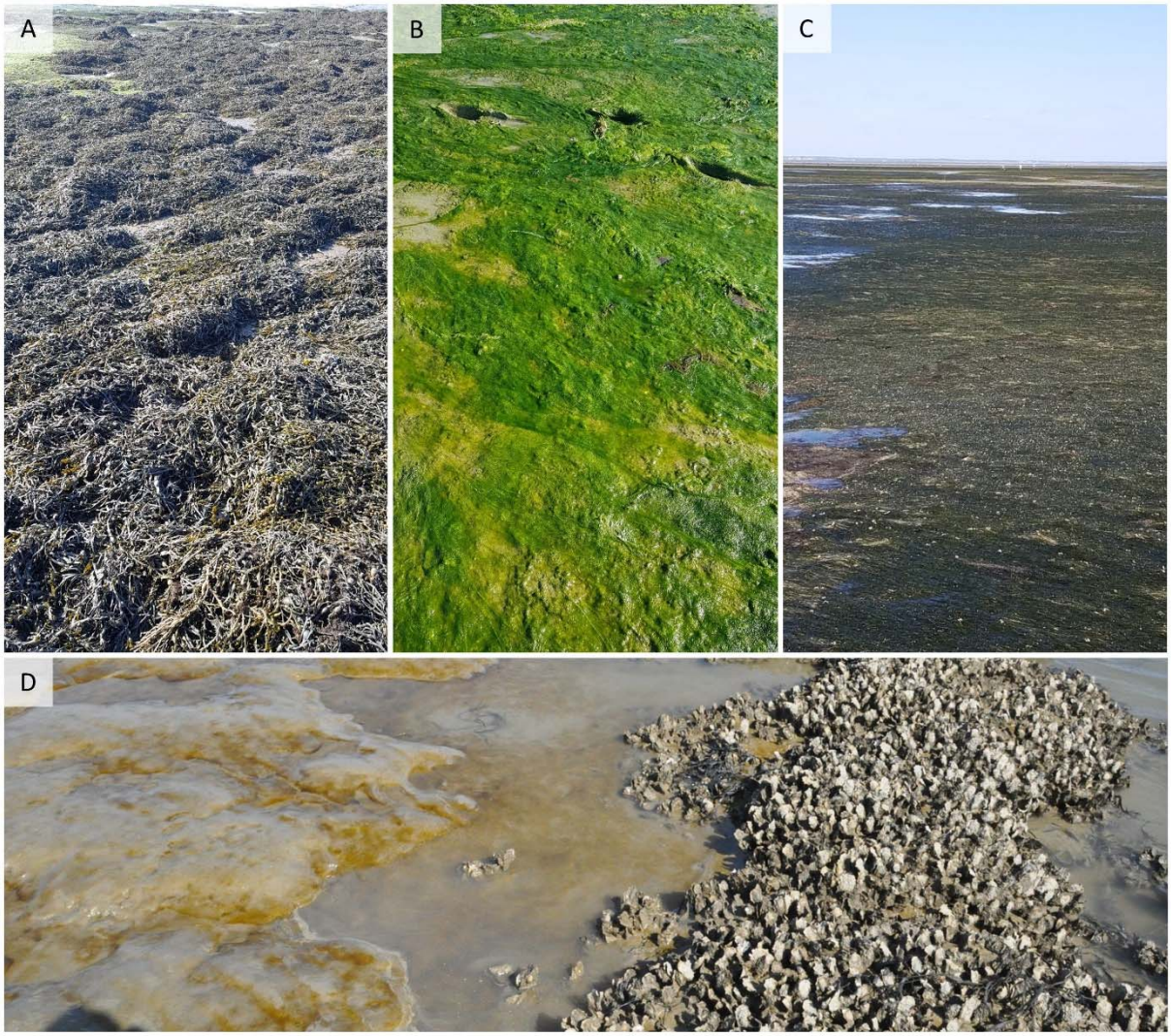

Fig. 2. Main primary producers of intertidal zones taken into account in this project: macroalgae, in particular brown mediolittoral algal belts (A), opportunistic green macroalgae (B), seagrass beds of marine angiosperms, in particular *Zostera noltei* (C), and microphytobenthos which forms biofilms on the surface of muddy sediments and wild oysters which can interact with these habitats (D).

Thesis guideline

Very high spatial & temporal resolution: study of micro-scale processes (Year 1)

The very high spatial resolution will be exploited from drones equipped with multispectral sensors to analyze two specific, but major sources of pressure applied to two intertidal habitats. The first source of pressure is the role of high concentrations of nutrients (especially nitrogen and phosphorus) on the development of microphytobenthos. This question has still not been resolved and has a direct impact on the development of a bioindicator of nitrogen inputs based on microphytobenthos (Oiry & Barillé 2021). An experiment to enrich the mudflat with nutrients *in situ* is planned to monitor by drone the biomass of benthic microalgae regarding to nutrient load. The second is the estimation of the impact of recreational bivalve hand fishing on *Zoltera noltei* meadows which is not yet quantifiable even with the high spatial resolution (2 m) of sensors such as Pléiades or Worldview. The aim is to exploit both the very high spatial (1cm) and temporal (several measurements during a tidal cycle) resolution to quantify these impacts. These two experiments will also be useful to acquire validation data for the mappings carried out at meso- and macro-scale. It will also be an opportunity to organize a spectral library and for the student to understand the spectral discrimination limits of plants sharing common pigmentary composition.

Evolution of four intertidal habitats over two decades (2000-2020) in a pilot site: seasonal and interannual variations (mesoscale) (Year 2)

Before Sentinel 2 constellation was operational, in 2015, allowing a high acquisition frequency of 3 to 5 days, temporal variations in intertidal habitats were poorly documented using remote sensing (Brito et al., 2013; van der Wal et al., 2010; Benyoucef et al., 2014). This general lack of temporal data explains why there are no time series spanning one or two decades that can be used to describe the evolution of intertidal vegetation subjected to global changes and anthropogenic pressures. However, in coastal and estuarine waters, there is a demand from the agencies in charge of implementing European directives (Water Framework Directive-WFD; Marine Strategy Framework Directive-MSFD) to link these habitats with pressures. We thus wish to analyze the seasonal and interannual variations of macroalgae, angiosperms, microphytobenthos and wild oyster reefs in the same pilot site including Bourgneuf bay and the Loire estuary from Sentinel 2 images (10 m, 2015 - present) acquired every 3-5 days supplemented by MODIS (2002 - present), MERIS (300 m, 2002 - 2012) and Sentinel 3 (300 m, 2017 - present) images acquired every 1 - 2 days. The simultaneous analysis of habitats could make it possible to detect possible interactions, in particular between wild oysters (*Crassostrea gigas*), an invasive species for about twenty years, and macroalgae which seem to be in decline on several sites (Le Bris et al. 2016). Seasonal variations and trends from time series will be analyzed using Dynamic Linear Models (DLM) (Hernandez-Farinas 2015).
The relationships with the pressure variables will be studied using data collected over the study period (2000-2020). The MMS laboratory has a database of environmental variables on the study site (contract with Météo France and data from the data-public.meteofrance.fr website). Additional pressure data will be obtained from the Naïades platform (naiades.eaufrance.fr) of the French Office for Biodiversity (OFB) and the Geological and Mining Research Office (BRGM). This last platform compiles data from water agencies. The data on the concentration of pollutants in the water will be collected on the Surval platform of the French Research Institute for the Exploration of the Sea (IFREMER). This platform makes it possible to consult and download quantitative and qualitative data relating to marine and coastal waters, taken from

the Quadrige database. This database has been designated as the Coastal Water Reference Information System by the Ministry of the Environment as part of the Water Information System. It brings together data on the concentration of the main pollutants in continental waters (metals and organotins, Polycyclic Aromatic Hydrocarbons (PAHs), Polychlorinated biphenyls, etc.) in the sediments.

Macro-scale mapping of intertidal habitats (Year 3)

In this last part, the objective is mapping intertidal habitats on a national and European scale using the Sentinel 2 constellation. We believe that Google Earth Engine could be a good tool, allowing to easily process a large number of satellite data. However, due to S2 reduced spectral resolution, we plan to use machine learning classification methods (Support Vector Machine, k-Nearest Neighbor, Random Forest) which have been successfully applied to identify intertidal vegetation with multispectral sensors (Murray et al. 2019; Martin 2020; Oiry & Barillé 2021; Traganos & Reinartz, 2018). These methods are based on the reflectances of the spectral bands in the visible and near infrared, multispectral indices, radar data, as well as the variables used by image segmentation techniques (Poursanadis et al. 2018). Microphytobenthos, macroalgae, seagrass, can be roughly identified with multispectral indices based on thresholds applied to vegetation indices (Méléder et al. 2003; Echappé et al. 2018, Zoffoli et al. 2020). However, additional information such as substrate type or bathymetry is often needed to facilitate discrimination (Barillé et al. 2011). Adding radar data could also be useful in identifying wild oyster reefs (Wang et al. 2021).

Two intertidal pilot sites (Fig. 3), namely Bourgneuf Bay and the Penzé estuary along the French Atlantic coast, will be used to develop the algorithms because (i) they host a diversity of habitats and (ii) are already documented with *in situ* mapping and spectroradiometry data. Three validation sites are envisaged from north to south Europe: the intertidal areas of the Wadden Sea in Germany, the bay of Mont Saint-Michel, the bay of Aveiro in Portugal. The structure of the intertidal vegetation between the different sites will be interpreted according to climatic gradients and anthropogenic pressures.

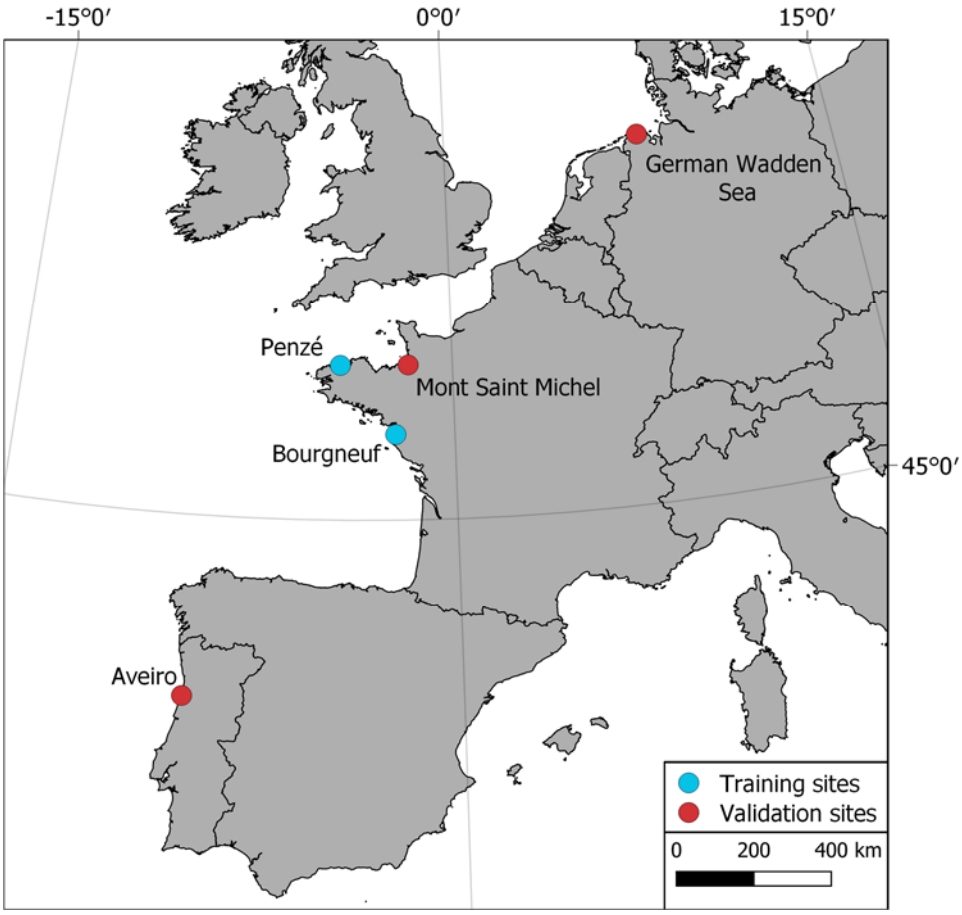

Fig. 3. Training and validation sites for the identification model of intertidal habitats build from Sentinel 2 images.

6. Partnership, project funding, materials available

National partnership : Debaine MCF CR – IGARUN (Université de Nantes)

The thesis work will benefit from a collaboration with Françoise Debaine from the Institute of Geography and Planning - IGARUN (University of Nantes) for her expertise in texture analysis with E-cognition software. This object-based analysis could complement the spectral-based classification for structured habitats such as wild oyster reefs.

International partnership:

Martin Gade (Lecturer) University of Hamburg for obtaining radar and validation data from the Wadden Sea site.

Joao Serodio (Professor) University of Aveiro, for validation data from Aveiro Bay

Dimosthenis Traganos (Dr) (German Center for Airborne and Space Sciences) for its expertise in Machine Learning and data processing using Google Earth Engine.

Victor Martinez-Vicente (Dr) (Plymouth Marine Laboratory) for interactions with the BiCOME project (see below).

Funding for operations of the project

A European project led by the Plymouth Marine Laboratory (PML) in collaboration with the University of Nantes and the German Center for Airborne and Space Sciences (Deutsches Zentrum für Luft- und Raumfahrt, DLR) was submitted in 2021 to the Space Agency European in response to the BIODIVERSITY + PRECURSORS: COASTAL ECOSYSTEMS call (https://down2earth.esa.int/opportunities/biodiversity-precursors/). The project is called "Biodiversity of the Coastal Ocean: Monitoring with Earth Observation (BiCOME)" and its main objectives are to identify and characterize the potential of remote sensing to study biodiversity at several coastal pilot sites and to assess the relevance of present and future sensors on pilot sites. The thesis may be linked to the project and benefit from 10 Keuros in operating costs (exchanges and reception with European partners).

Materials available

Archive images of SPOT, Landsat, MERIS, hyperspectral images Hyspex, DESIS

Spectroradiometers ASD FieldSpec, Ocean Optics

Drones Phantom IV et Matrice 200 with multispectral sensors

Spectral library of benthic microalgae

High Performance Liquid Chromatography (HPLC) for the analysis of pigments

Collection of benthic microalgae and devices for carrying out experimental measurements.

Satellite image processing software ENVI

Geographic Information System Software MapInfo, ArcGis, eCognition

Data processing software PRIMER, CANOCO

7. Publications of supervisors related to the subject

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