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Brice Corrigeux, Marche Brunelle, Mauricio Camargo, Christophe Bachmann,
Clémence Chaudron

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Identification of sensor technologies with the potential to support roadside ecosystem services

Corrigeux Brice
Université de Lorraine, ERPI, F-54000
Nancy, France
brice.corrigeux@univ-lorraine.fr

Marche Brunelle
Université de Lorraine, ERPI, F-54000
Nancy, France
brunelle.marche@univ-lorraine.fr

Camargo Mauricio
Université de Lorraine, ERPI, F-54000
Nancy, France
mauricio.camargo@univ-lorraine.fr

Bachmann Christophe
NOREMAT S.A, F-54710 Ludres,
France
C.BACHMANN@noremat.fr

Chaudron Clémence
UMR 1434 SILVA, Université de
Lorraine, AgroParisTech, INRAE,
Faculté des Sciences et Technologies,
F-54506, Vandoeuvre les Nancy, France
clemence.chaudron@univ-lorraine.fr

Abstract — In perpetual development, roads are creating a vast network with harmful ecological effects. However, vegetative strips that border them, called roadsides, can mitigate, and even provide additional ecosystem services to the society (biodiversity preservation, water and air filtration, ...). Mainly for security reasons, these roadsides must be regularly maintained. Inappropriate roadside management can lead to the decrease in ecosystem services (spread of invasive plants, habitats destruction or modification of the environment by soil enrichment among others). As roadside maintenance is highly recommended, the aim of this review is to identify technological solutions allowing to reduce management effects on ecosystem services provided by roadsides. Based on a systematic review of the scientific literature, five sensor technologies solutions were finally selected: the detection of rare, protected, or invasive plant species, the detection of animals, the automated control of ditches, the assessment of biomass quantity and carbon storage and the assessment of cultural services provided by roadsides.

Keywords— sensors, roadsides, management, ecosystem services, environment

I. INTRODUCTION

Road infrastructures already represent a significant area at the world scale and 25 million kilometers of roads should be built until 2050 [1]. This road network in expansion has substantial ecological effects on environment: loss and fragmentation of habitats, light and noise pollution, chemical pollution of air and water, direct mortality of wild animals due to car collision [2]. However, considering the importance of roads in our society, the mitigation of these negative effects seems to be the most realistic solution [3]. These authors demonstrate that roadsides, grass strips along roads, represent an opportunity to mitigate these effects. Indeed, due to their location between district roads and several environments, as well as their composition (plant and animal species, ditches, ...), roadsides can provide several ecosystem services, for example, by playing the role of habitat and ecological corridor for some species.

The awareness of the existence of these services, along with a global development of an ecological thought of nature preservation in the society, are pushing local authorities to take an interest in these environmental aspects. This

questioning is illustrated by the change in roadside management practices over time. Even though new practices can reduce the negative effects of intensive roadside management, these ones are still significant.

Roadside maintenance is required for safety reasons, and it seems to be hard to move to management practices considering environmental aspects. The emergence of new technologies may be a lever to mitigate the impacts of roadside management on ecosystems. Indeed, the fast development of different sensor technologies may represent an opportunity of positive environmental contribution for the management of roadsides. Low-cost manufacturing and more reliable performance make the sensor technologies applicable in many different areas/fields that are almost only limited by our imagination [4]. Several studies have already explored possible applications of sensor technologies with an ecological purpose [5]. Sensors allow to accumulate a lot of data of diverse information and is a precious source for decision making in environmental management. So, this research aims to identify sensor technologies allowing to conciliate management of roadsides and enhancement of their ecosystem services, i.e., to realize a maintenance of roadsides more sustainable, which does not alter or at least alter less the services provided by roadsides.

This work develops a systematic review of the literature with the aim of exploring the main technologies that could be used for the maintenance of roadsides through a graphic representation of bibliometric maps. This type of representations makes possible a semantic analysis of the bibliography based on co-occurrence data. The visualization tool based on clustering algorithm, VOSviewer, will be utilized [6].

II. EXISTING THEORIES & PREVIOUS WORK

A. Ecosystem services provided by roadsides

Roadsides are characterized by the presence of three elements: (i) the berm, the area closest to the roadway, (ii) the ditch, whose role is to evacuate rainwater and (iii) the slope which make the junction between the ditch and the adjacent area (forest, culture,...) [7] (Fig.1).

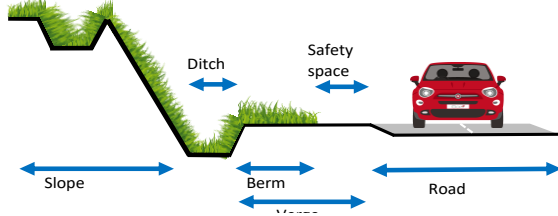


Fig.1 Description of roadsides [7]

Several research have focused on ecosystem services provided by roadsides [3], [8]. Ecosystem services can be divided into four categories: self-maintenance services, provisioning services, regulation services and cultural services [9]. However, roadsides can also provide disservices to the society. The table 1 synthesizes all ecosystem services and disservices provided by roadsides.

1) *Self-maintenance services*: Self-maintenance services correspond to services allowing ecosystems to be able to last over time and to continue to provide other ecosystem services [9]. As regard to roadsides, several self-maintenance services have been identified. The grass strips characteristic of roadsides enhance pollination which is important for the reproduction of many plant species. A large population of pollinator insects also contribute to increase yield of adjacent arable fields [8]. Moreover, roadsides can preserve water resources by facilitating the infiltration and the retention of rainwater in the ground [10]. Roadsides also participate to the preservation of biodiversity. They represent a favorable habitat for many animal and plant species [11]. Moreover, because of their low area/perimeter ratio, roadsides are particularly influenced by adjacent habitats [12]

that can represent sources of propagules. Roadsides can also constitute ecological corridors, facilitating the movement of several plant and animal species [13]. The dispersal of plant species can be facilitated along roadsides by the transport of cars or by the mowing machine used in roadside management [14]. In addition, mowing machine can also increase the dispersal of seeds from roadsides to adjacent habitats [14].

2) *Provisioning services*: Provisioning services correspond to products that can be used in order to meet a need [9]. Roadsides constitute an interesting area for bioenergy production [15]. Indeed, they can provide green waste that can be composted or used as feedstock for energy production [16]. It is also now possible to collect the mown biomass and to use it in anaerobic digestion sector for the production of biogas [17]. However, the ways of reusing roadsides waste are still being explored. Green waste appear to be a promising starting material for the direct extraction of valuable compounds, for chemical and fermentative conversion into basic chemicals as well as for the manufacture of functional materials such as electrodes used in electro-biotechnological applications by carbonization [16].

3) *Regulation services*: Regulation services are services that mitigate or regulate natural phenomena [9]. Roadsides and more particularly ditches play a major role in the regulation of water level. They also play an important role for the evacuation of rainwater during heavy rains [10]. Some types of vegetation in ditches allow water filtration and then to obtain water of better quality by extracting pesticides and heavy metals from the water before their infiltration into the ground [18]. The vegetation of roadsides also acts as a regulator of climate change by storing CO₂ through photosynthesis process [19].

4) *Cultural services*: Cultural services are unmaterial profits that humanity can earn from ecosystems [9]. From this point of view, roadsides structure the landscape and participate to its diversity. During hot periods when staying under the sun become unbearable, and more specifically in town, roadsides can create more pleasant climate by the presence of trees. Indeed, in addition to create shaded areas,

TABLE I. ECOSYSTEM SERVICES AND DISSERVICES OF ROADSIDES

<p style="text-align: center;">Self-maintenance services</p> <p>Pollination : enhance the development of a varied flora, favorable to insect's development</p> <p>Preservation of water resources : improve water filtration and retention</p> <p>Preservation of biodiversity : suitable habitats and corridors for several plant and animal species. Harbor remarkable and protected species.</p>		<p style="text-align: center;">Regulation services</p> <p>Pest control : constitute a refuge area for culture auxiliary</p> <p>Water level regulation : ditches can regulate the water level</p> <p>Water quality : play the role of phyto-purifier thanks to the vegetation</p> <p>Climate regulation : participate to carbon storage</p>	
<p style="text-align: center;">Provisioning services</p> <p>Source of biomass : the vegetation can serve as an energetic resource (firewood, methanization)</p>	<p style="text-align: center;">Cultural services</p> <p>Landscape's diversity : participate to the landscape's diversity. Structuring element of the landscape</p> <p>Fight against heat island : trees provide shaded areas and spread humidity</p>	<p style="text-align: center;">Disservices</p> <p>Presence of allergenic plants : some species like ambrosia can provoke severe allergies</p> <p>Infrastructure's deterioration: the vegetation can be a cause of deterioration for the road or the vehicles</p> <p>Lowering of culture yield: weeds can spread into adjacent arable fields</p>	

trees also spread humidity in the air by the phenomenon of evapotranspiration [13].

5) *Disservices*: Ecosystem disservices represent all the negative effects of roadsides on environment and on society. The presence of allergen plant species in roadsides can lead to breathing difficulties, conjunctivitis and even eczema [20]. Roadsides can also be a source of deterioration of infrastructures when/if trees fall on the road [3]. Finally, roadsides can facilitate the dispersal of weeds in adjacent arable fields, especially if plants have already produced their seeds when they are mown. Mowing machine can, in this case, project seeds in the direction of the field [14] which could then establish and develop themselves, colonize the field and compete with crops.

B. Roadside management practices and their impacts

Roadsides need a particular management. Indeed, if the vegetation is not regularly mown and pruned, drivers' visibility can be reduced, and this can increase road accident risks. Signage, and all other security elements, must stay apparent. Roadsides are maintained to allow drivers to drive in safety or to stop/park on it in case of emergency. They must also be maintained for reducing fire starting risks [3], and flooding risks [13]. Consequently, the maintenance of roadsides by local authorities is compulsory. Several practices chosen by local authorities, can be implemented and can have different impacts.

We can differentiate two different kinds of regimes: the standard regime and the environmentally-friendly regime.

Standard regime, correspond to an intensive management, i.e. that the number of mowing per year is particularly high in order to ensure road users visibility, particularly at bends, intersections and on narrow roads, etc. [21]. On average, roadsides are mown three times per year, sometimes more and the height of mowing is low: between 5 and 8 centimeters [22].

At the opposite, the environmentally-friendly regime consists in rationalizing the practices of roadside management [21], it aims to take into account negative impacts that the standard regime can have on the environment, and to mitigate them. In France, it includes an increase in the height of mowing, a reduction in the number of mowing (2 mowing in average per year, in spring and at

the end of summer), a delayed in the first date of mowing, and a differentiation of the practices according to the environment characteristics (present species, protected areas, parts of roadside) [22]. In addition, an exportation of the biomass can be carried out.

The choices that are made on the practices have several impacts at three different levels: the social level, the ecological level, and the economic level [3].

First, the mowing frequency have several impacts on ecosystem services delivered by roadside verges. A high mowing frequency can reduce pollination, biodiversity preservation [23] and pests' control services but can also mitigate infrastructures' deterioration and ensure road users' security. A high mowing frequency can also increase the management costs and the energy consumption compared to low mowing frequency.

Then, the choice of the mowing height directly impacts the preservation of the biodiversity and the maintenance cost: a low mowing height weaken the biodiversity and provoke damage on the material [22]. A high mowing height can permit to mitigate these consequences and reduce the energy consumption.

With the environmentally-friendly regime, a choice is made to delay the summer mowing. This choice has impacts on several ecosystem services: a late mowing allows most species to complete their life cycle which can increase plant diversity [24]. By allowing the vegetation to grow at a significant height, the roadsides can constitute a good refuge for wildlife [3]. This regime favors the development of the flora until its flowering and therefore offers a landscape with various colors [25]. This decision can also have negative effects as a lowering of the culture yield by spreading seeds in crops and of road users' security in some cases.

An environmentally-friendly regime also includes a differentiation of practices according to areas and needs. It enhances services of biodiversity preservation, pollination and landscape's diversity but also mitigates the presence of allergenic plants because a specific treatment is done [26].

The last choice that we evaluated as having an impact on the ecosystem of roadsides is the export of the mown biomass. In this case, the soil is not enriched in nitrogen and plant diversity can be increased [27]. This practice also enhances the development of pollinator insects, indeed, in areas where this regime is implemented, the average number of inflorescences and flower-visiting insects within roadsides

TABLE II. IMPACTS OF STANDARD REGIME ON ECOSYSTEM SERVICES/DISSERVICES

Completed practices	Ecosystem services	Ecosystem disservices		Advantages	Disadvantages
	<i>Disadvantaged</i>	<i>Accentuated</i>	<i>Mitigated</i>		
Augmentation of mowing frequency	Pollination, biodiversity preservation, pests' control		Infrastructures' deterioration	Road users' security, clean landscape	Increase of management costs, energy consumption and greenhouse gas emission
Low mowing height					Increase of material maintenance costs and energy consumption
Undifferentiated mowing	Remarkable species	Presence of allergenic plants (in some cases)	Infrastructures' deterioration		
No export of the mown biomass	Biodiversity preservation				Soil enrichment, development of nitrophilous species

TABLE III. IMPACTS OF ENVIRONMENTALLY FRIENDLY REGIME ON ECOSYSTEM SERVICES/DISSERVICES

Completed practices	Ecosystem services		Ecosystem disservices		Advantages	Disadvantages
	<i>Favorized</i>	<i>Disadvantaged</i>	<i>Accentuated</i>	<i>Mitigated</i>		
Delay of summer mowing	Biodiversity preservation, pollinator insects' development, landscape		Lowering of culture yield			Road users' security lowered in some cases
Higher mowing height	Biodiversity preservation				Material maintenance costs decrease Energy consumption decrease	
Reduction of the number of mowing activities	Biodiversity preservation, ecological corridor, pollinator insects' development, landscape's diversity				Greenhouse gas emission decrease, Budget for the mowing activities reduced	
Differentiation of practices according to areas and needs	Biodiversity preservation, pollinator insects' development, landscape's diversity			Presence of allergenic plants		
No collection of the mown biomass		Biodiversity preservation				Soil enrichment Development of nitrophilous species
Collection of the mown biomass	Biodiversity preservation, source of biomass				Valorization of green waste Ditches and pipes maintenance costs reduction	

can be higher than under the standard mowing regime [28]. Exporting the biomass also reduces the needs of maintenance concerning ditches and pipes [29] and somehow compensates a part of the costs and the energy consumption linked to mowing activities thanks to the valorization of the biomass [17].

All these different impacts on ecosystem services/disservices as well as the advantages/disadvantages of each mowing regimes are synthesized in table II and table III.

This study on different management practices underlines that they can have several impacts on ecosystem services. Indeed, a modification of the practices of standard regime (Table II) towards an environmentally-friendly regime with or without biomass export (Table III) seems to be an opportunity to restore some ecosystem services provided by roadsides. In the continuity of these changes in management practices, this article focuses on the improvement of the roadside management by seeking if sensor technologies (mature or emerging) can be able to evaluate or enhance the ecosystem services provided by roadsides.

III. METHODS

A. Research question

The purpose of this study is to answer to the question: how can existing sensor technologies be implemented in roadside management with the purpose of supporting roadside ecosystem services?

B. Applied research method

With this aim, we set up a research with three different steps (Fig.2). The first one is a systemic review of the literature with the purpose of identifying the most used sensor technologies in sectors close to roadside management. To realize this systemic review of the literature, we used the software VOSviewer that permits to map the frequently used terms and to create co-occurrence relationships. This

systematic review can there again be decomposed into three different parts.

First, as the roadside management is not a highly treated subject, the employed strategy has been to broaden the subject. So, the first step of this systematic review was to determine which sensor technologies were used in applications related to the vegetation and their specific use. We decided to use the database Web of Science, and the Boolean equation used was as follows: (Title-Abs-Key (sensor*) AND Title-Abs-Key (vegetation)). Studied publications were published between 1950 and 2021.

For the second part, we decided to get closer to the thematic of roadside management by changing one of the keywords of the equation which became: (Title-Abs-Key (sensor*) AND Title-Abs-Key (mow*)). This modification led us to identify the sensor technologies which are used in agriculture and for the maintenance of green areas and to have an overview on how they are used.

The last part of the systematic review is about the identification of sensor technologies which are used to measure and enhance ecosystem services. So, the research equation for this part is: (Title-Abs-Key (sensor*) AND Title-Abs-Key ("ecosystem services")).

The second step of the research strategy consisted in studying applications that were made of sensor technologies. With this aim, we read scientific articles about ecosystem services that we can find in the ecosystem of roadsides. So, we were able to understand how these technologies are used to measure and enhance ecosystem services.

The purpose of the last step of this study was to make the links between the identified technologies and the ecosystem services provided by roadsides.

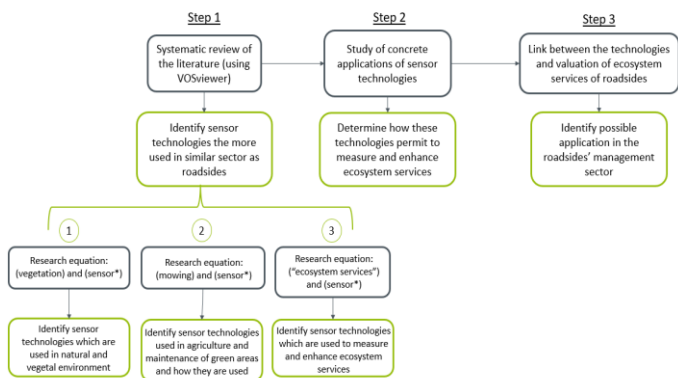


Fig.2 Research strategy

IV. FINDINGS

A. Collected data.

We found a total of 9059 articles focusing on the use of sensor related to the vegetation. We can note that the number of articles published on this subject is constantly increasing year by year (Fig.3).

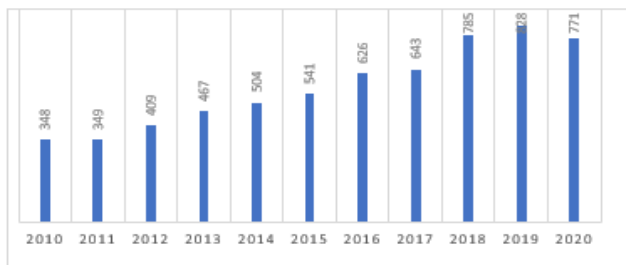


Fig.3 Evolution of the number of published articles per year (Source: Web of Science)

The main funders of research on the subject are the NSFC (National Natural Science Foundation of China), the NASA (National Aeronautics Space Administration) and the European commission.

Research areas could be identified in order of importance: imagery sciences (3328 results), environmental sciences

(2975 results), geology (2130 results), agriculture (1135 results), physical geography (737 results), and meteorology (538 results).

By analyzing these results with VOSviewer, we highlighted that the most studied technology was the remote sensing. It consists in determining, from a distance, the characteristics of an object by receiving radiation reflected or emitted by this one. Remote sensing gathers several technologies that are cited in articles studied, for example: LIDAR (Light Detection And Ranging), RADAR (Radio Detection And Ranging), photogrammetry and multispectral and hyperspectral camera. All these technologies are principally used in forest management or in precision agriculture to control the state and the development of the vegetation.

We found a total of 176 articles focusing on the use of sensor related to mowing activities. The main terms used in these articles are represented in Fig.4 as well as the links of co-occurrences between them.

Seven clusters were identified, and their description is shown in Table IV.

TABLE IV. CLUSTERS AND KEYWORDS IDENTIFIED BY VOSVIEWER

Cluster	Principal keywords	Keywords related
Cluster 1 <i>Red color, 8 items</i>	Automation	Aboveground biomass, agriculture, leaf-area index, obstacle detection, remote sensing, validation, vegetation indexes
Cluster 2 <i>Green color, 5 items</i>	Robotics	Mobile robot, navigation, sensor-based coverage, vehicles
Cluster 3 <i>Dark blue color, 5 items</i>	Precision agriculture	Alfalfa, biomass, grass growth, wheat
Cluster 4 <i>Yellow color, 5 items</i>	System	Algorithms, mowat-wilson syndrome, mutations, neurons
Cluster 5 <i>Purple color, 4 items</i>	Electrochemical sensor	Dopamine, nanoparticle, sensor
Cluster 6 <i>Light blue color, 4 items</i>	Variability	Dew, model, sensors
Cluster 7 <i>Orange color, 3 items</i>	Spectral reflectance	Nitrogen, vegetation

Thus, an overview of the use of sensors in the field of natural areas management is obtained: sensors are mainly used to optimize tasks and thus to increase efficiency. The environmental problematic has not really been approached. It seems interesting to assess if the use of sensors can lead to a more environmentally-friendly management regime of roadsides, this could improve our knowledge of ecosystem services provided by roadsides and the impacts of

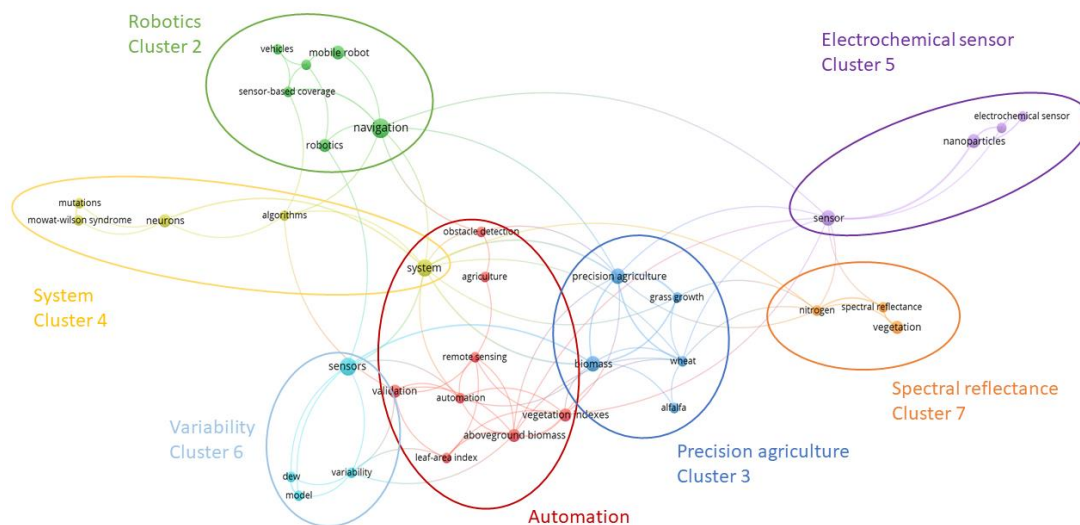


Fig.4 VOSviewer map for step 2 (Research: sensor* and mowing; 176 results)

management practices on roadsides' ecosystems. We will now interest ourselves on the way that identified technologies are used to measure and enhance ecosystem services.

B. Analysis of collected data

1) *The LIDAR*: Firstly, the LIDAR technology is used to quantify provisioning services. The LIDAR is indeed used to quantify biomass quantity of trees in a forest. Data collected this way give good estimations of wood production because LIDAR allows a precise measure of the trees' height [30]. In the same way, this technology is also used to estimate crop production [31]. Depending on the structure and the density of the studied vegetation, a part of the radiation emitted by the LIDAR penetrate the vegetation and is reflected by the ground. By analyzing the time difference between the return of the two signals, it is possible to estimate the height of the observed vegetation. In some cases, the laser radiation does not penetrate the vegetation, so the ground level must either be measured by another mean, either be estimated by creating a digital terrain model (DTM) from an extrapolation of other measurable points. With the same process, it is possible to measure the carbon storage service of the vegetation because it is relative to the biomass quantity [30].

Secondly, the LIDAR technology can also be used to estimate pollination service. Several studies have mapped bees' densities [32], [33]. This technology has not been used for measuring ecosystem services yet, but the existing technologies would allow it.

Finally, the LIDAR can be used to evaluate cultural services and more particularly the one provided by landscapes. Researchers interested in this subject, have identified landscapes' characteristics appreciated by people providing a cultural ecosystem service [34]. This experiment led to the characterization of the qualities that are important for the people as beaches, body of water, terrain slope, etc.

2) *The RADAR*: In the first place, the RADAR technology can be used in the same way as the LIDAR, for measuring the biomass quantity or the stored carbon quantity in the vegetation. The main difference is that the RADAR is placed on a satellite and not on a UAV, the data cost is therefore cheaper than with the LIDAR because there is no material investment. The accuracy of RADAR estimations is also lower than LIDAR estimations [35]. The choice of technology depends on the objectives to be achieved and on the financial means available.

Then, the RADAR can also be used to study insects' migration. Indeed, researchers have shown that it is possible to measure the mass and the length of moving insects [36]. This can allow to identify species moving from an area to another and to anticipate impacts of this kind of movements. Insects migrations represent a biomass and nutrients transfer and can provide pest control service and be important for pollination [37].

The RADAR technology is also a possibility to study flooding risks [38]. Among all these remote sensing technologies, the RADAR has the advantage of penetrating

the cloud cover and not being disturbed by rain. It allows to follow flooding that happened most of the time during heavy rain events. This method use data collected during past events, allows to map flooding areas/zones and to identify areas with more flooding risks.

3) *Multispectral and hyperspectral cameras*: This remote sensing technology can be used to identify plant species. For example, it is used in the sector of forest management in order to differentiate and to map different tree species present in a given area [39].

Hyperspectral imagery is also studied for its potential capacity as a tool for fire prevention [40]. By studying the composition and the structure of the vegetation, researchers have been able to simulate fire propagation and to evaluate the risks of this event in a given area with an accuracy of 93%.

Thanks to this technology, it is also possible to control the health of observed plants. This is particularly interesting within the framework of forest management. For example, we can identify areas under water stress or that are unhealthy [41].

4) *Conventional cameras*: Conventional cameras can be used for the recognition of some plant species. With a recognition algorithm, the technology allows to identify, to count and localize the species. For this type of use, the camera is placed on an Unmanned Aerial Vehicle (UAV) which flies above the studied area. Once the images are collected, they are processed by an artificial intelligence system which, after being "trained", is able to identify the species of interest [42].

5) *Infrared cameras*: The infrared cameras allow to distinguish the different objects according to their temperature; they can be used to detect warm blooded animals even when visibility conditions are not optimal. In [43], these cameras can be used to study the behavior of bat species and so establish if they play a role in the pollination of some trees.

C. Discussion

The purpose of this discussion is to show how the identified technologies can be adapted to the roadside management sector in order to achieve a more environmentally-friendly regime.

1) *Mapping of rare, protected, or invasive plant species*: Roadsides are a favorable habitat for biodiversity, for fauna as well as for flora. Sensor use in management practices could help to detect rare, protected, and invasive plant species. Then, by adjusting management practices, we could be able to preserve or limit their population. To do this, several technologies seem to be suitable: first, remote sensing which is already used to identify some rare species [44]. For this technology, satellites or UAV are generally used for collecting data, because they allow to observe areas which are difficult to access such as dense forest canopy and isolated natural areas. In the case of roadsides, the area is easily accessible, thereby maintenance vehicles can be equipped with these kinds of devices and can collect data. Technologies

used in this type of applications are conventional cameras and multispectral or hyperspectral cameras. The choice is based on specific biological characteristics of the target species compared to other species. One of the limits of these technologies is their sensibility to meteorological conditions and shaded areas which affect their accuracy [45].

Collecting these kinds of data could help implementing extensive management practices. For example, invasive plants clusters could be mapped and the evolution of their size, number and location could be continuously followed. This could help understanding how these plants spread in the territory and to set specific actions on strongly affected areas in order to limit their spread and reduce their presence. This type of data could also allow to follow the dynamic of rare and protected species and adjust management practices.

2) *Detection of animals*: Several animal species use roadsides as a habitat, for example insects, reptiles, amphibians, birds, and small mammals. In order to preserve them during mowing activities, the use of thermal camera can be considered. It is used in agricultural sector for human obstacles avoidance in the development of automated vehicles [46] and could be adapted to roadside mowing. However, this technology concerns only warm-blooded animals like birds and small mammals. Moreover, other existing technologies cannot detect insects, reptiles, and amphibians through dense vegetation. For these species, it can be wise to work out predictive detection systems [44].

The use of LIDAR can also be considered in this context. Indeed, we have previously seen that this technology could allow to measure and to map bees' density [33]. The acquisition of these kinds of data on roadsides would permit, for example, to know the periods of strong activity of the bees and so, to avoid mowing during these periods in order to preserve bees. In addition, we could investigate which areas bees use the most and identify their characteristics (e.g., plant species present, their abundance and flowering period). RADAR is also used to study insects' migration [36], it represents a potential tool for roadside management, and could be used in the same way as LIDAR.

3) *Automated ditches control*: Roadside ditches evacuate rainwater. It is therefore a crucial element during heavy rains, especially in urban areas where most of the ground is waterproofed by concrete. When the mown biomass is left on the ground, it can obstruct the canalization infrastructure like pipes and bridges, leading to flooding problems. Despite their importance, ditches are rarely controlled due to the lack of efficient control techniques. Therefore, some scientists have addressed this issue by using LIDAR technology to realize DTM of the studied ditches and verify if they are functional [10]. This analysis allows, by the simple passage of a vehicle, to evaluate their capacity to evacuate water and to propose potential modifications of their profile.

In addition, plant species recognition techniques (see section 5.1), could be used to check water infiltration capacity of the vegetation composing ditches. Some species are able to absorb potential water pollutants and their identification

could allow to measure the capacity of ditches to improve water quality and so to provide a regulation service.

4) *Evaluation of biomass quantity and carbon storage*: The technologies previously identified allow to quantify provisioning service provided by forests, by estimating the biomass quantity available. Even if the first role of roadsides is not to be a source of biomass, this service can be considered. Thanks to LIDAR and RADAR technologies, we could collect data on biomass quantity contained in trees, and also on vegetation useful for methanization or composting. Information on vegetation quantity could be interesting when the environmentally-friendly regime with biomass export is carried out. This would allow to plan mowing dates when vegetation quantity is the highest, or simply to optimize transport activity by estimating biomass quantity that will be collected for transport optimization for example.

In addition, the evaluation of biomass quantity in roadsides can allow to assess their role in storing carbon and so their contribution to the fight against global warming.

5) *Evaluation of cultural service provided by roadsides*: It could be interesting to study how roadsides are perceived by humans and which characteristics are important for providing a cultural service (as shown by [34]) The presence of trees, hedges, and/or flowers, but also of artificial elements like fences and electric pylons, could represent key characteristics. The use of LIDAR technology combined with a photographic survey, could allow to obtain data on roadsides characteristics influencing the cultural service.

Fig.5 summarized all these possible applications and show the links that we established with the different impacted ecosystem services.

6) *Global integration of these practices to roadside management*: Although all these technologies exist, it can be complex/difficult to include them in existing roadside management practices.

To assess whether it is possible, we can examine technologies' maturity:

The LIDAR technology has reached a very good state of maturity because it is used in a lot of sectors as building and civil engineering or the automobile sector with the development of autonomous vehicles. These sectors cannot allow any mistakes, it means that LIDAR technology is functional and accurate in a favorable environment. However, the vegetation of roadsides could reduce the level of accuracy of this technique.

The RADAR technology is globally very well controlled, but this is less true in the case of obstacle detection. Indeed, this technology is not as accurate as the LIDAR for locating obstacles. It is used for reversing RADAR of vehicles, but the information only concerns the presence of an object in the area. RADAR that would permit to accurately localize obstacles in a green environment are still under study. The market is therefore quite reduced, and the technology is hard to get.

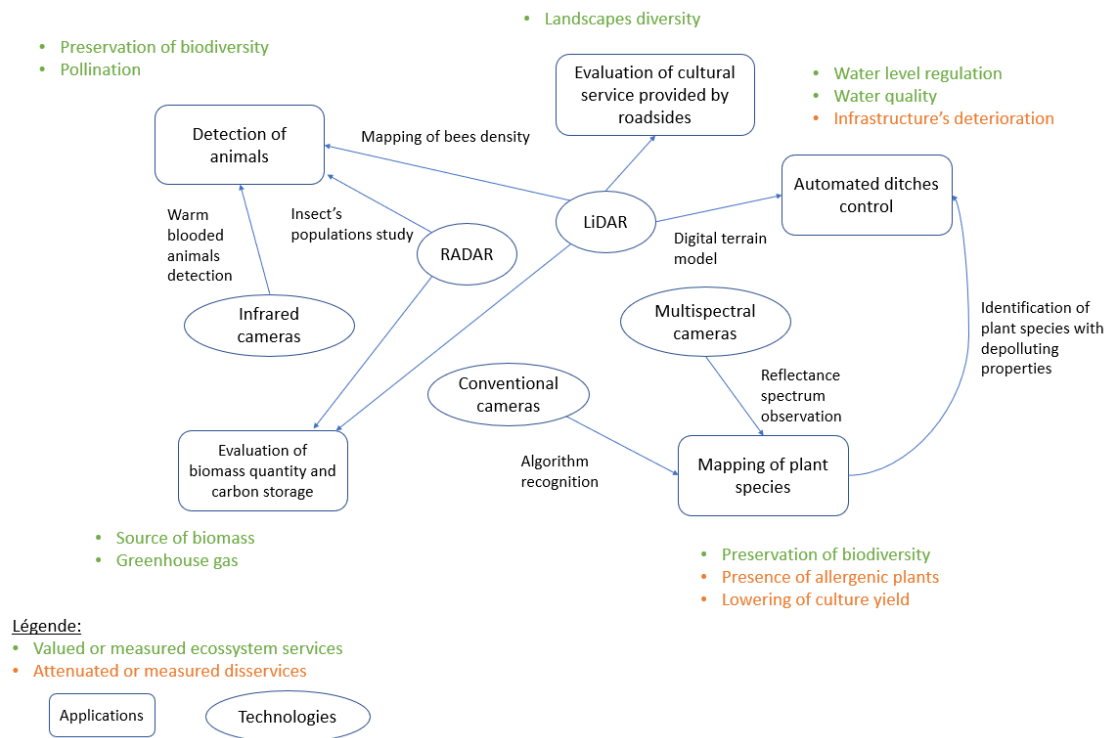


Fig.5 Summary of the possible applications of sensor in roadside management

Concerning the three types of cameras (conventional, multispectral, and infrared), they all are at a high maturity level, and they are easily accessible on the market. However, the information processing phase is under development, particularly the use of conventional camera for object recognition and, in our case, plant species recognition.

From a global point of view, the main difficulty in integrating these technologies into roadside management sector is the financial aspect. Sensor technologies are not likely to be regularly used and they represent a significant investment for local authorities. An operating approach could allow to minimize the financial investment. For example, sharing the material at a regional scale could be a solution to limit the investments by local authorities.

V. CONCLUSION

We assessed the potential for integrating sensor technologies into roadside management practices. The main goal was to identify existing technologies that can allow to estimate ecosystem services provided by roadsides. We have seen that several ways of using sensor technologies exist for a better understanding of nature and ecosystem services provided by roadsides. Several of these techniques that are used in different sectors can be adapted to roadside management. The mapping of rare, protected, or invasive species, the detection of animals, the automated control of ditches, the assessment of biomass quantity and of carbon storage, and the assessment of cultural services provided by roadsides, could be possible with these new technologies. Carrying out these different measures would highlight the important role that roadsides can play in the provision of ecosystem services. In addition, by enhancing our knowledge on this ecosystem and its functioning, we could be able to

optimize its management and to derive maximum benefit from it.

This research study proposes possible technical solutions for the implementation of a more sustainable management of roadsides. Additional research on each technical solutions are needed to assess their effectiveness. The main limits that need to be addressed are the financial constraints, because the presented technologies can require large investments. In addition, their effective use in a vegetated environment such as roadsides, needs to be investigated. To evaluate the investment to realize, it is important to quantify the potential benefits we can get from the valuation of some ecosystem services because these services can be financially quantified. To limit investments by local authorities, sharing material or using open-source data or software can be considered. Future studies should focus on potential benefits of using the identified technologies, by considering the investment required and trying to reduce it.

REFERENCES

- [1] J. Dulac, « Global Land Transport Infrastructure Requirements ». 2013.
- [2] R. T. T. Forman *et al.*, « Road Ecology: Science and Solutions ». 2003.
- [3] B. B. Phillips, J. M. Bullock, J. L. Osborne, et K. J. Gaston, « Ecosystem service provision by road verges », *J. Appl. Ecol.*, vol. 57, n° 3, p. 488-501, mars 2020, doi: 10.1111/1365-2664.13556.
- [4] Chee-Yee Chong et S. P. Kumar, « Sensor networks: Evolution, opportunities, and challenges », *Proc. IEEE*, vol. 91, n° 8, p. 1247-1256, août 2003, doi: 10.1109/JPROC.2003.814918.
- [5] Y. Kishino, Y. Yanagisawa, Y. Shirai, S. Mizutani, T. Suyama, et F. Naya, « Agile Environmental Monitoring Exploits Rapid Prototyping and In Situ Adaptation », *IEEE Pervasive Comput.*, vol. 16, n° 2, p. 61-71, avr. 2017, doi: 10.1109/MPRV.2017.34.
- [6] N. J. van Eck et L. Waltman, « Software survey: VOSviewer, a computer program for bibliometric mapping », *Scientometrics*, vol. 84, n° 2, p. 523-538, août 2010, doi: 10.1007/s11192-009-0146-3.

- [7] S. C. Bautista Rodriguez, C. P. Mauricio, M. Laure, et B. Christophe, « Sustainable Management of Roadside: Towards a Research Agenda », in *2018 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC)*, Stuttgart, juin 2018, p. 1-9. doi: 10.1109/ICE.2018.8436326.
- [8] B. B. Phillips *et al.*, « Enhancing road verges to aid pollinator conservation: A review », *Biol. Conserv.*, vol. 250, p. 108687, oct. 2020, doi: 10.1016/j.biocon.2020.108687.
- [9] « Millenium Ecosystem Assessment ». 2005.
- [10] C.-C. (Barry) Lee et N. G. Gharaibeh, « Automating the evaluation of urban roadside drainage systems using mobile lidar data », *Comput. Environ. Urban Syst.*, vol. 82, p. 101502, juill. 2020, doi: 10.1016/j.compenvurbysys.2020.101502.
- [11] R. T. T. Forman, « Road ecology: A solution for the giant embracing us », p. 3.
- [12] D. Le Coeur, J. Baudry, et F. Burel, « Field margins plant assemblages: variation partitioning between local and landscape factors », *Landsc. Urban Plan.*, vol. 37, n° 1-2, p. 57-71, juin 1997, doi: 10.1016/S0169-2046(96)00370-2.
- [13] O. S. O'Sullivan, A. R. Holt, P. H. Warren, et K. L. Evans, « Optimising UK urban road verge contributions to biodiversity and ecosystem services with cost-effective management », *J. Environ. Manage.*, vol. 191, p. 162-171, avr. 2017, doi: 10.1016/j.jenvman.2016.12.062.
- [14] C. Chaudron et F. Isselin-Nondedeu, « Assessing the effects of mowing machinery on seed dispersal pattern: a test of two methods of seed tracking », *Bot. Lett.*, vol. 164, n° 4, p. 413-423, oct. 2017, doi: 10.1080/23818107.2017.1369901.
- [15] A. Voinov, O. Arodudu, I. van Duren, J. Morales, et L. Qin, « Estimating the potential of roadside vegetation for bioenergy production », *J. Clean. Prod.*, vol. 102, p. 213-225, sept. 2015, doi: 10.1016/j.jclepro.2015.04.034.
- [16] A. Langsdorf, M. Volkmar, D. Holtmann, et R. Ulber, « Material utilization of green waste: a review on potential valorization methods », *Bioresour. Bioprocess.*, vol. 8, n° 1, p. 19, févr. 2021, doi: 10.1186/s40643-021-00367-5.
- [17] A. K. P. Meyer, E. A. Ehimen, et J. B. Holm-Nielsen, « Bioenergy production from roadside grass: A case study of the feasibility of using roadside grass for biogas production in Denmark », *Resour. Conserv. Recycl.*, vol. 93, p. 124-133, 2014.
- [18] A. L. Collins, D. E. Walling, R. W. Stroud, M. Robson, et L. M. Peet, « Assessing damaged road verges as a suspended sediment source in the Hampshire Avon catchment, southern United Kingdom », *Hydro. Process.*, vol. 24, n° 9, p. 1106-1122, avr. 2010, doi: 10.1002/hyp.7573.
- [19] N. R. Bouchard, « The capacity of roadside vegetated filter strips and swales to sequester carbon », *Ecol. Eng.*, p. 6, 2013.
- [20] A. B. Singh et C. Mathur, « Climate Change and Pollen Allergy in India and South Asia », *Immunol. Allergy Clin.*, vol. 41, n° 1, p. 33-52, 2021.
- [21] S. Bautista Rodriguez *et al.*, « Towards Smart and Suitable Management of Roadside: System Dynamics in the Era of Industry 4.0 », *Sustain. Oper. Comput.*, 2020.
- [22] SETRA, « Fauchez mieux, le fauchage raisonné », p. 24, 2009.
- [23] L. Klimes^ˆ et J. K. Ova, « The effects of mowing and fertilization on carbohydrate reserves and regrowth of grasses: do they promote plant coexistence in species-rich meadows? », p. 20.
- [24] U. Song, D. Son, C. Kang, E. J. Lee, K. Lee, et J. S. Park, « Mowing: A cause of invasion, but also a potential solution for management of the invasive, alien plant species *Erigeron annuus* (L.) Pers », *J. Environ. Manage.*, vol. 223, p. 530-536, oct. 2018, doi: 10.1016/j.jenvman.2018.06.057.
- [25] J. Lampinen et N. Anttila, « Reconciling road verge management with grassland conservation is met with positive attitudes among stakeholders, but faces implementation barriers related to resources and valuation », *J. Environ. Plan. Manag.*, vol. 64, n° 5, p. 823-845, avr. 2021, doi: 10.1080/09640568.2020.1785405.
- [26] I. Milakovic, K. Fiedler, et G. Karrer, « Management of roadside populations of invasive *Ambrosia artemisiifolia* by mowing », *Weed Res.*, vol. 54, n° 3, p. 256-264, 2014, doi: 10.1111/wre.12074.
- [27] R. H. Marrs, « Soil Fertility and Nature Conservation in Europe: Theoretical Considerations and Practical Management Solutions », in *Advances in Ecological Research*, vol. 24, Elsevier, 1993, p. 241-300. doi: 10.1016/S0065-2504(08)60044-6.
- [28] C. Chaudron, R. Perronne, P. Bonnin, et T. Rattier, « An agro-environmental mowing regime favors the number of inflorescences and flower-visiting insects but not ground beetles of herbaceous boundaries of arable fields », *Basic Appl. Ecol.*, vol. 48, p. 1-10, nov. 2020, doi: 10.1016/j.baae.2020.06.002.
- [29] S. Bautista, M. Camargo, et C. Bachmann, « Sustainable roadside management from an innovative approach to ecosystem services and bioenergy generation », in *2020 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC)*, juin 2020, p. 1-6. doi: 10.1109/ICE/ITMC49519.2020.9198647.
- [30] Y. Z. Ayanu, C. Conrad, T. Nauss, M. Wegmann, et T. Koellner, « Quantifying and Mapping Ecosystem Services Supplies and Demands: A Review of Remote Sensing Applications », *Environ. Sci. Technol.*, vol. 46, n° 16, p. 8529-8541, août 2012, doi: 10.1021/es300157u.
- [31] B. B. Koné, « Utilisation de données Lidar pour la caractérisation des grandes cultures: cas du maïs et du soja », 2007.
- [32] J. A. Shaw *et al.*, « Polarization lidar measurements of honey bees in flight for locating land mines », *Opt. Express*, vol. 13, n° 15, p. 5853, 2005, doi: 10.1364/OPEX.13.005853.
- [33] D. S. Hoffman, A. R. Nehrir, K. S. Repasky, J. A. Shaw, et J. L. Carlsten, « Range-resolved optical detection of honeybees by use of wing-beat modulation of scattered light for locating land mines », *Appl. Opt.*, vol. 46, n° 15, p. 3007, mai 2007, doi: 10.1364/AO.46.003007.
- [34] D. B. Van Berkel *et al.*, « Quantifying the visual-sensory landscape qualities that contribute to cultural ecosystem services using social media and LiDAR », *Ecosyst. Serv.*, vol. 31, p. 326-335, juin 2018, doi: 10.1016/j.ecoser.2018.03.022.
- [35] M. A. Tanase, R. Panciera, K. Lowell, C. Aponte, J. M. Hacker, et J. P. Walker, « Forest Biomass Estimation at High Spatial Resolution: Radar Versus Lidar Sensors », *IEEE Geosci. Remote Sens. Lett.*, vol. 11, n° 3, p. 711-715, mars 2014, doi: 10.1109/LGRS.2013.2276947.
- [36] R. Wang *et al.*, « Migratory Insect Multifrequency Radar Cross Sections for Morphological Parameter Estimation », *IEEE Trans. Geosci. Remote Sens.*, vol. 57, n° 6, p. 3450-3461, juin 2019, doi: 10.1109/TGRS.2018.2884926.
- [37] K. R. Wotton *et al.*, « Mass Seasonal Migrations of Hoverflies Provide Extensive Pollination and Crop Protection Services », *Curr. Biol.*, vol. 29, n° 13, p. 2167-2173.e5, juill. 2019, doi: 10.1016/j.cub.2019.05.036.
- [38] G. Schumann et G. Di Baldassarre, « The direct use of radar satellites for event-specific flood risk mapping », *Remote Sens. Lett.*, vol. 1, n° 2, p. 75-84, juin 2010, doi: 10.1080/01431160903486685.
- [39] J. Mäyrä *et al.*, « Tree species classification from airborne hyperspectral and LiDAR data using 3D convolutional neural networks », *Remote Sens. Environ.*, vol. 256, p. 112322, avr. 2021, doi: 10.1016/j.rse.2021.112322.
- [40] I. Keramitsoglou, C. Kontoes, O. Sykioti, N. Sifakis, et P. Xofis, « Reliable, accurate and timely forest mapping for wildfire management using ASTER and Hyperion satellite imagery », *For. Ecol. Manag.*, vol. 255, n° 10, p. 3556-3562, mai 2008, doi: 10.1016/j.foreco.2008.01.077.
- [41] V. Singh, « Application of Hyperspectral Remote Sensing in Forest Health Assessment and Mapping », 2018.
- [42] C. Zhang, P. M. Atkinson, C. George, Z. Wen, M. Diazgranados, et F. Gerard, « Identifying and mapping individual plants in a highly diverse high-elevation ecosystem using UAV imagery and deep learning », *ISPRS J. Photogramm. Remote Sens.*, vol. 169, p. 280-291, nov. 2020, doi: 10.1016/j.isprsjprs.2020.09.025.
- [43] S. A. Aziz *et al.*, « Pollination by the locally endangered island flying fox (*Pteropus hypomelanus*) enhances fruit production of the economically important durian (*Durio zibethinus*) », *Ecol. Evol.*, vol. 7, n° 21, p. 8670-8684, nov. 2017, doi: 10.1002/ece3.3213.
- [44] C. Cerrejón, O. Valeria, P. Marchand, R. T. Caners, et N. J. Fenton, « No place to hide: Rare plant detection through remote sensing », *Divers. Distrib.*, 2021.
- [45] A. Piron, B. Dumont, et M.-F. Destain, « La vision artificielle: une méthode d'avenir pour la reconnaissance automatisée des plantes adventices? », *Biotechnol. Agron. Société Environ.*, vol. 15, n° 4, p. 597-610, 2011.
- [46] M. F. Kragh *et al.*, « Fieldsafe: dataset for obstacle detection in agriculture », *Sensors*, vol. 17, n° 11, p. 2579, 2017.