

Review

# Remote Sensing of Environmental Drivers Influencing the Movement Ecology of Sympatric Wild and Domestic Ungulates in Semi-Arid Savannas, a Review

Florent Rumiano <sup>1,2,\*</sup> , Elodie Wielgus <sup>3,4,5,6,7</sup> , Eve Miguel <sup>8,9</sup>, Simon Chamaille-Jammes <sup>6,7,10</sup>, Hugo Valls-Fox <sup>6,7,11,12</sup> , Daniel Cornélis <sup>13,14</sup>, Michel De Garine-Wichatitsky <sup>4,5,15</sup> , Hervé Fritz <sup>7,16,17</sup>, Alexandre Caron <sup>4,5,18</sup>  and Annelise Tran <sup>1,2,4,5</sup> 

<sup>1</sup> CIRAD, UMR TETIS, F-97490 Sainte-Clotilde, Réunion, France; annelise.tran@cirad.fr

<sup>2</sup> TETIS, Univ Montpellier, AgroParisTech, CIRAD, CNRS, INRAE, 34090 Montpellier, France

<sup>3</sup> Division of Biology and Conservation Ecology, Manchester Metropolitan University, Manchester M1 5GD, UK; elodie.wielgus@stu.mmu.ac.uk

<sup>4</sup> CIRAD, UMR ASTRE, F-34398 Montpellier, France; michel.de\_garine-wichatitsky@cirad.fr (M.D.G.-W.); alexandre.caron@cirad.fr (A.C.)

<sup>5</sup> ASTRE, Univ Montpellier, CIRAD, INRAE, 34090 Montpellier, France

<sup>6</sup> CEFÉ, Univ. Montpellier, CNRS, EPHE, IRD, Univ. Paul Valéry Montpellier 3, 34090 Montpellier, France; simon.chamaille@cefe.cnrs.fr (S.C.-J.); hugo.valls-fox@cirad.fr (H.V.-F.)

<sup>7</sup> LTSER France, Zone Atelier CNRS “Hwange”, Hwange National Park, Bag 62 Dete, Zimbabwe; herve.fritz@cnrs.fr

<sup>8</sup> MIVEGEC, Univ. Montpellier, IRD, CNRS, 34090 Montpellier, France; eve.miguel@ird.fr

<sup>9</sup> CREES Centre for Research on the Ecology and Evolution of Disease–Montpellier, 34090 Montpellier, France

<sup>10</sup> Mammal Research Institute, Department of Zoology & Entomology, University of Pretoria, 0083 Pretoria, South Africa

<sup>11</sup> CIRAD, UMR SELMET, PPZS, 6189 Dakar, Senegal

<sup>12</sup> SELMET, Univ. Montpellier, CIRAD, INRAE, Institut Agro, 34090 Montpellier, France

<sup>13</sup> CIRAD, Forêts et Sociétés, F-34398 Montpellier, France; daniel.cornelis@cirad.fr

<sup>14</sup> Forêts et Sociétés, Univ. Montpellier, CIRAD, 34090 Montpellier, France

<sup>15</sup> Faculty of Veterinary Medicine, Kasetsart University, Bangkok 10900, Thailand

<sup>16</sup> UCBL, UMR CNRS 5558, University of Lyon, 69007 Lyon, France

<sup>17</sup> World Wildlife Fund, Washington, DC 20037-1193, USA

<sup>18</sup> Faculdade de Veterinaria, Universidade Eduardo Mondlane, 257 Maputo, Mozambique

\* Correspondence: florent.rumiano@cirad.fr; Tel.: +33-638-2526-72

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**Abstract:** Interfaces between protected areas and their peripheries in southern Africa are subject to interactions between wildlife and livestock that vary in frequency and intensity. In these areas, the juxtaposition between production and conservation land uses in a context of increasing anthropisation can create issues associated with human-wildlife coexistence and raises concerns for biodiversity conservation, local development and livelihoods. This literature review aimed at addressing the need to consolidate and gather in one article current knowledge on potential uses of satellite remote sensing (SRS) products by movement ecologists to investigate the sympatry of wildlife/domestic ungulates in savanna interface environments. A keyword querying process of peer reviewed scientific paper, thesis and books has been implemented to identify references that (1) characterize the main environmental drivers impacting buffalo (*Syncerus caffer caffer*) and cattle (*Bos taurus* & *Bos indicus*) movements in southern Africa environments, (2) describe the SRS contribution to discriminate and characterize these drivers. In total, 327 references have been selected and analyzed. Surface water, precipitation, landcover and fire emerged as key drivers impacting the buffalo and cattle movements. These environmental drivers can be efficiently characterized by SRS, mainly through open-access

SRS products and standard image processing methods. Applying SRS to better understand buffalo and cattle movements in semi-arid environments provides an operational framework that could be replicated in other type of interface where different wild and domestic species interact. There is, however, a need for animal movement ecologists to reinforce their knowledge of remote sensing and/or to increase pluridisciplinary collaborations.

**Keywords:** African savanna; animal movements; earth observation imagery; remote sensing; sympatric wild and domestic ungulates; wildlife-livestock interface

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## 1. Introduction

In Africa, human populations living at the edge of protected areas have significantly increased in recent years [1,2]. This burst in human population is a challenge for biodiversity conservation in protected areas (PA) and livestock production in adjacent communal lands (CL) where these land uses coexist [3]. At the PA-CL interfaces, interactions between wildlife, people and their livestock frequently occur [4,5] even when park or veterinary fences, largely detrimental to wildlife movements, exist [6–8]. This growing number of interactions potentially increases human/wildlife coexistence related issues [3] such as competition for resources inside/outside protected areas [9], predation of livestock by wild carnivores [10], crop destruction by wildlife [11], and risk of pathogen transmission between wild and domesticated species [12–14]. These complications associated with human/wildlife coexistence raise challenges for biodiversity conservation and local development. They impact local communities' livelihoods and well-being [15–18], and threaten the sustainable coexistence between stakeholders involved in the management of these land-uses. In this context, identifying and characterizing environmental drivers that condition animal movements in space and time is essential to assess the potential opportunities and threats associated with wild/domestic interactions in PA-CL interfaces.

The potential for SRS applications, regarding environment monitoring in general and animal conservation in particular, has been largely stressed [19,20]. Indeed, SRS techniques provide an increasing number of sensors [21–26] that may characterize the environmental drivers impacting animal movements at different space and time scales. Moreover, SRS offers continuous temporal follow-up data in areas where in-situ data are nonexistent and/or difficult to collect [27], as it is the case in the savanna landscapes in southern African PA-CL interfaces [28]. In these heterogeneous open environments with high variability in soil composition, topography, and subject to dynamic processes such as rainfall, fire, climate change, herbivory and human impacts [29–31], SRS could provide viable tools to predict biophysical measurements of cover, density, and biomass of savanna vegetation [32,33]. However SRS also faces difficulties in retrieving vegetation spectral response due to soil background, vegetation shadow, standing dead vegetation occurring in these arid and semi-arid areas [34,35]. Despite these limitations, combining SRS with recent advances in telemetry technology is key to assess wildlife/domestic animal interactions in savanna landscapes, especially at PA-CL interfaces [36–38].

The African buffalo (*Syncerus caffer caffer*) and cattle (*Bos taurus* & *Bos indicus*) are keystone species for conservation and production systems in southern African PA-CL interfaces. The understanding of their functional ecology constitutes an applied example on how SRS can be efficiently used to design a framework of animal movement analyses. The African buffalo is one of the “Big Five” [39] and contributes to consumptive and non-consumptive tourism [40,41], provides a source of proteins and income for local communities [42] and is an important member of the ungulate guild who shapes habitat heterogeneity in and outside protected areas where the human presence is low [43–46]. Cattle, in subsistence farming communities, provide draught power, source of protein, cash incomes, safety net and social status [47–49]. Buffalo and cattle are both grazer ungulates, close phylogenetically, sharing common resources (i.e., forage and water) [50], and are thus likely to overlap in range and compete for resources, particularly in environments where resources are spatially segregated

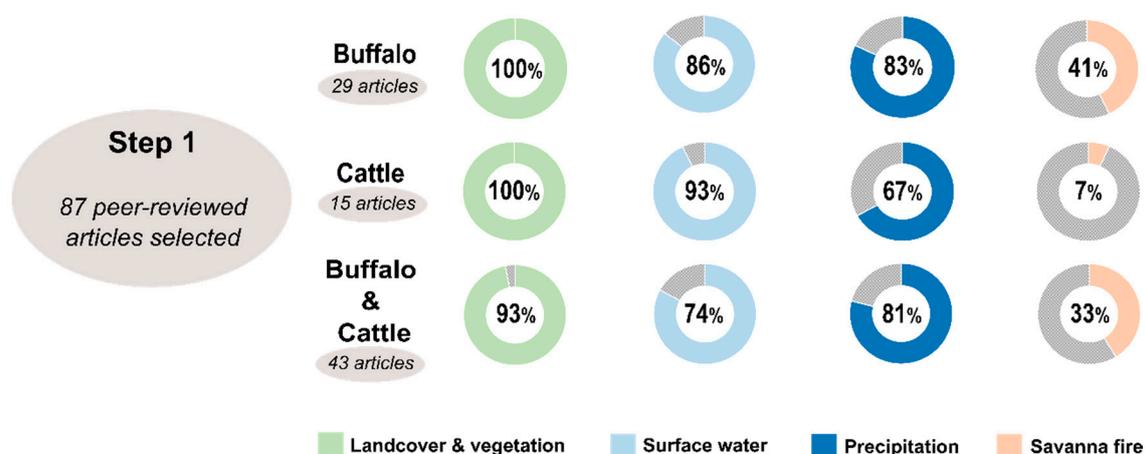
(e.g., savannas) [51,52]. Both species rely on their behavior and the management of the land use by humans to cope with constrained access to natural resources (e.g., access to artificial water, forage intake by the herder) [53,54]. Their shared use of space increases the likelihood of direct (i.e., the use of the same space at the same time) and indirect (i.e., the use of the same space at different times) contacts, which in turn promotes the risk of pathogen transmission [12,55–58], a threat to farmers and biodiversity conservation [4,13]. Given this complex ecological context, characterizing buffalo and cattle habitats to understand their movements in space and time in conjunction with currently available SRS applications and methodologies is necessary.

In this review article, we aim at (1) reviewing the main environmental drivers impacting buffalo and cattle movements in southern Africa interface environments, (2) describing the SRS contribution to discriminate and characterize these drivers in southern Africa interfaces. The underlying objective is to facilitate the uses of SRS by movement ecologists in order to improve wildlife/domestic animals management and conservation in different types of savanna interfaces across the globe. It is adding and completing previous works that focused on the link between SRS, environmental challenges and animal movement but in a wider ecological context [20,59].

## 2. Review Article Methodology

A literature review of peer-reviewed articles, thesis and books in English (such as defined in Grant and Booth (2009) [60]) has been conducted on the following topics: (i) behavioral and movement ecology of buffalo and cattle in southern Africa; (ii) existing remote sensing tools allowing the discrimination in time and space of determined environmental drivers. The Web of Science database was used to retrieve relevant references via a two steps keyword querying process without time constraint. At each step, a systematic screening based on the title and the abstract was first conducted to select the articles, books or thesis for full-text reading. Selected references bibliographies have also been read to extract additional relevant articles, book or thesis.

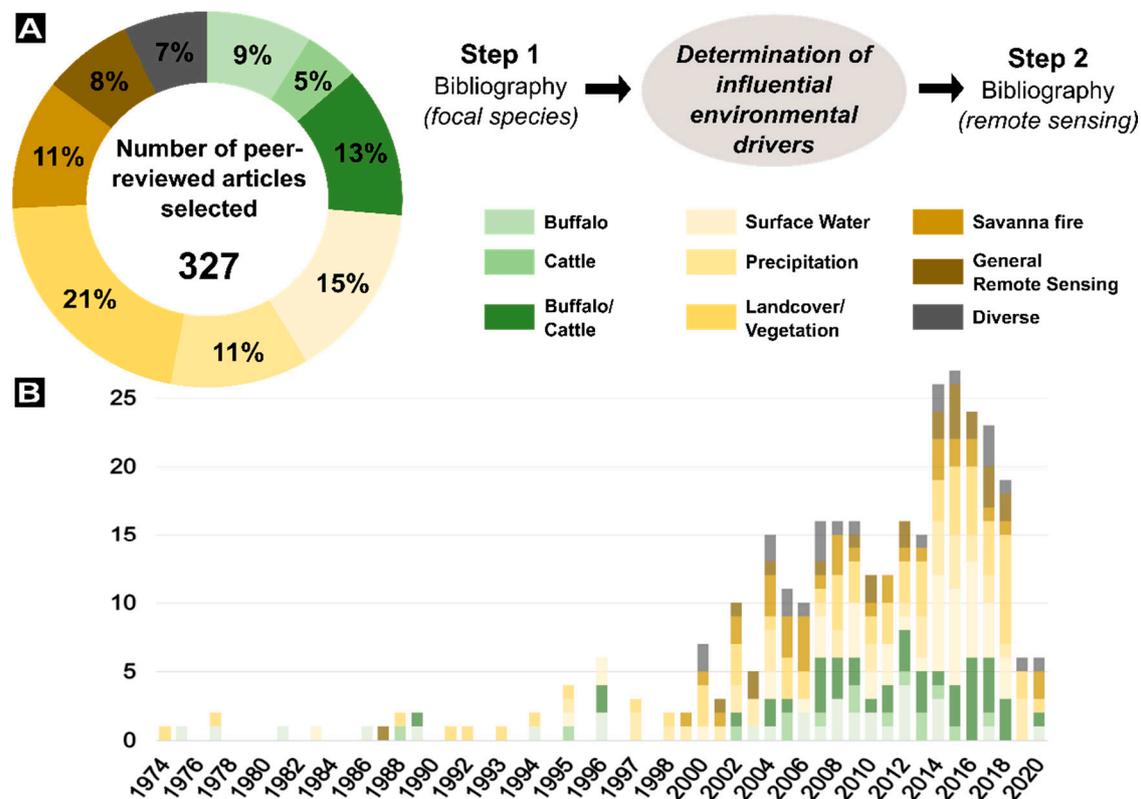
The first step was to discriminate the environmental drivers impacting buffalo and cattle movements in space and time. The different keywords combined in no particularly order in the first step were “buffalo”; “syncerus caffer”; “cattle”; “bos taurus”; “bos indicus”; “ungulates”; “southern africa”; “movement”. The search resulted in 787 references. After abstract screening and the removal of replicates, 87 peer-reviewed articles, thesis and books from 1975 to 2020 were included in the review (Figure 1). Among them, 29 (33.3%) articles concerned buffalo only, 15 (17.2%) cattle only, and 43 (49.5%) both species. Landcover & Vegetation, surface water, precipitation and savanna fire emerged as main environmental drivers impacting focal species (buffalo & cattle) (Figure 1).



**Figure 1.** Environmental driver statistics of the step 1 bibliography. The percentage of articles identifying the environmental drivers of animal movements among all the peer-reviewed selected articles is presented according to the species considered (buffalo only, cattle only, buffalo & cattle).

The second step was to define the existing methodologies in remote sensing to characterize the different environmental drivers previously determined. The different keywords combined in no particular order in the second step were all the environmental drivers determined in the first step: “surface water”; “precipitation”; “rainfall”; “vegetation”; “fire” with the addition of the following keywords: “remote sensing”; “Earth observation imagery”; “landcover”; “land-use”; “spectral index”; “radar”; “optical”; “savanna”. The search resulted in 1140 references and, after abstract screening and the removal of duplicates, 240 articles from 1974 to 2020 were included in the review.

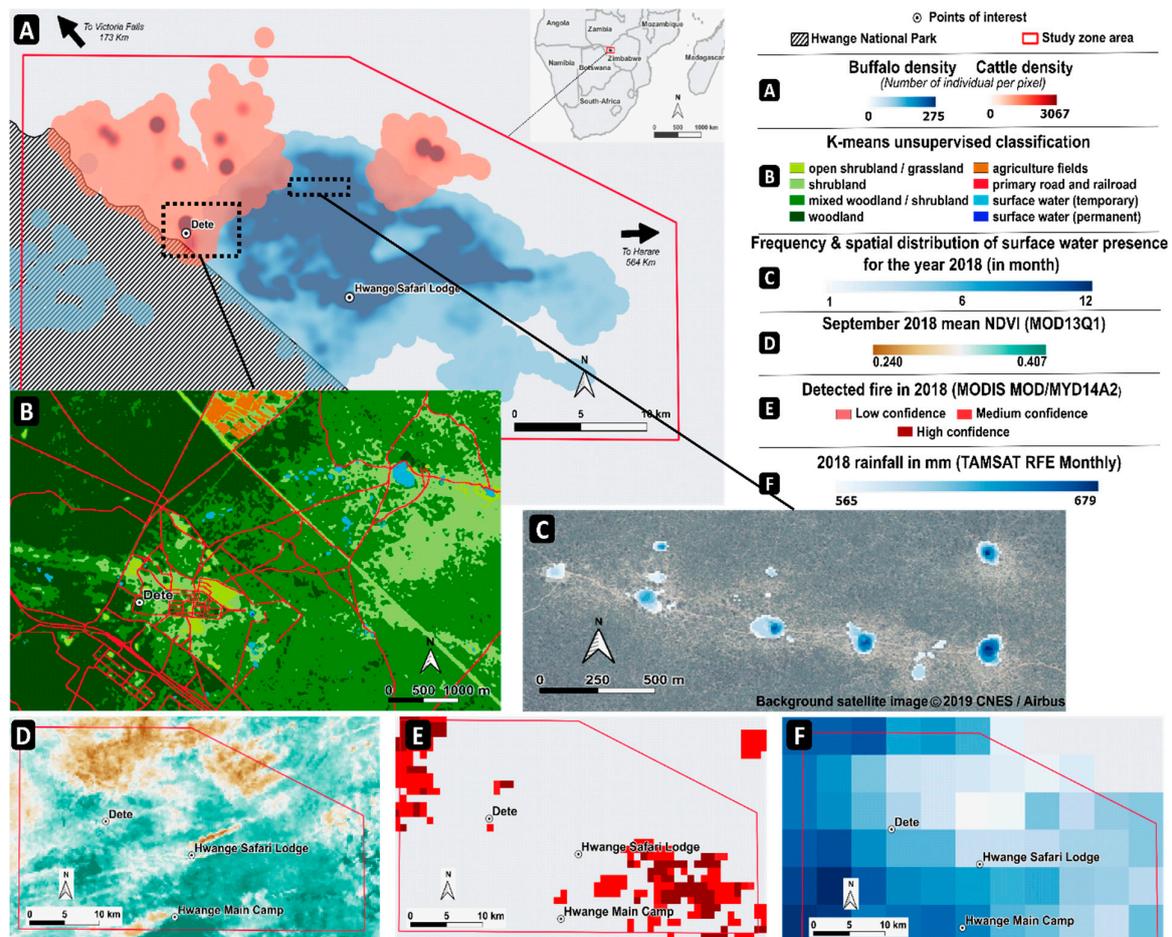
In total, 327 articles from 1974 to 2020, divided into 9 categories, have been selected and used as reference in this paper (Figure 2A). The “diverse” category includes the articles with general themes close to the study, but which cannot fit into the other specified categories. Two thirds of the selected peer-reviewed articles are about SRS, with a majority of them specifically focusing on Landcover & vegetation and surface water (Figure 2A). We observed an increase in publications related to SRS since the early 2000s and a steady frequency of peer-reviewed articles focusing on buffalo and cattle (Figure 2B).



**Figure 2.** Statistics and chronology of the article bibliography by topic category. (A) The ring diagram represents the percentage of each category in relation to the total number of reviewed articles. (B) The horizontal axis of the histogram corresponds to the published year of the selected articles. The vertical axis corresponds to the number of published articles according to their respective categories.

### 3. Environmental Drivers Influencing the Movements of Buffalo and Cattle and the Satellite Remote Sensing Tools to Characterize them

The main environmental drivers (Landcover/vegetation, surface water, savanna fire and precipitation) identified through the reviewing process (Section 2) are illustrated through this section using the example of a buffalo/cattle interface localized in HNP, Zimbabwe (Figure 3). In this particular context, the two focal species interact at the interface between a national park and an adjacent CL (Figure 3A) where habitats cover a wide variety of environments and natural resources.



**Figure 3.** Illustrative examples of SRS-derived environmental drivers of buffalo and cattle movement in HNP, Zimbabwe (refer to supplementary materials for a complete description of the data used). (A) Map of the buffalo and cattle density based on GPS data set for both species (number of individual per pixel in the HNP interface ecosystem at 5m spatial resolution) [12]. (B) K-means unsupervised landcover classification map of Dete municipality next to HNP derived from Sentinel-2 imagery with a 10 m spatial resolution [61]. (C) Frequency and distribution of surface water presence at 10 m spatial resolution obtained via the Random Forest (RF) algorithm applied on a sentinel-2 image of March 2018 after the application of atmospheric corrections [61]. (D) Normalized Difference Vegetation Index (NDVI) map with a 250 m spatial resolution from the Moderate-Resolution Imaging Spectroradiometer (MODIS). (E) Map of fire detected in 2018 using the MOD14A2 Fire product with a 1 km spatial resolution. (F) Map of the yearly precipitation estimations by the Tropical Applications of Meteorology using SATellite data (TAMSAT V3.0) product with a 4 km spatial resolution [62,63].

### 3.1. Landcover

#### 3.1.1. How Landcover and Vegetation Influences Cattle and Buffalo Movements

Landcover (cropland, forest, surface water, artificial cover, bare soil, human infrastructures, . . . ) affects animal movements because it reflects differences in resource availability, habitat structure preferences and ease of travel [64–66]. Buffalo and cattle are ruminants and predominantly grazers [67–69]. They are associated with open environments, where grass species are more abundant [70], and the spatial and temporal variability of fodder resource drives the foraging responses of both species [71]. Seasonal shifts in the composition of their diet are common due to the availability of grass species [72,73]. During the dry season, i.e., when quantity and quality of food resources decrease, buffalo and cattle adopt a selective and opportunistic switching between different

types of habitat or concentrated feeding close to water sources [72,74]. Buffalo tend to avoid areas used by cattle due to strong dietary overlap [75,76], the presence of human activities, and can travel long distances to find suitable feeding resources during the dry season [71,77]. During the wet season, buffalo tend to select available feeding resources located close to watering points, limiting their daily travelled distances [70]. Cattle can range further away from their enclosures on their own, sometimes into protected areas in search of quality forage when the season is dry and when there is no fences surrounding the park [78]. In contrast, during the wet season, cattle focus on accessible and available shrub vegetation or low lying herbaceous vegetation at proximity of their respective enclosure and inside natural park in some instance [37]. Cattle are however prevented to enter agricultural fields during the growing season [79].

### 3.1.2. SRS Basics for Characterizing and Classifying Landcover

SRS is widely used to assess landcover [80–84]. Different types of satellite sensors (Table 1) record the electromagnetic radiations which characterize the landcover, may this be the radiation reflected (optical sensors), the radiation emitted (thermal infrared and passive microwave sensors) or the radiation scattered (active radar sensors) [85]. Their characteristics (spatial resolution, revisit time period, spatial coverage, data availability, spectral resolution—see Table 1) define their capacities to map different land cover types on a given study area.

**Table 1.** Small subset of Earth observation satellite systems allowing data acquisition that can potentially be used in the field of animal movement ecology.

Optical Remote Sensing Satellites							
Sensor Resolution	Satellite	Spatial Resolution	Revisit Time Period	Nb of Spectral Bands	Access	Data Availability	Used in Buffalo/Cattle Ecological Studies
Low Resolution	NOAA	1.1 Km Bands 1–2	2 times a day	5	Open-source	1978–present	[86,87]
	MODIS	250 m/bands 3–7 500 m/bands 8–36	2 times a day	36	Open-source	1999–present	[29,54,67,79,87–89]
	Suomi NPP	1 km Bands II-5 375 m/bands M1-16	2 times a day	22	Open-source	2012–present	-
	Envisat MERIS Sentinel-3	750 m 300 m 300 m	3 days 2 days	15 21	Open-source Open-source	2002–2012 2016–present	- -
Medium Resolution	Landsat	Pan* 15 m/MS* 30 m/TIR* 60 to 100 m	16 days	4–11	Open-source	1972–present	[11,37,88,90]
	Sentinel-2	VNIR* 10 m/SWIR* 20 m/ACB* 60 m	5 days	13	Open-source	2015–present	[91]
	Aster	VNIR 15 m/SWIR 30 m/TIR 90 m	16 days	14	Open-source	1999–present	-
High Resolution	Spot	Pan 1.5 to 2.5 m/MS 6 to 10 m	26 days	4–5	Licensed	1986–present	[26]
	Ikonos	Pan 1 m/MS 4 m	1.5–3 days	5	Licensed	1995–2015	[54,92]
	Rapideye	MS 5 m	1–5.5 days	5	Licensed	2008–present	[26]
	ZY-3	Pan 2.1 m/MS 5.8 m	5 days	4	Licensed	2012–present	-
	GF-1/GF-2 PlanetScope-DOVEs	MS 5 m MS 3 m	4–5 days Daily	5 4	Licensed Licensed	2013–present 2017–present	- -
Very-high Resolution	Quickbird	Pan 0.61 m/MS 2.24 m	2.7 days	5	Licensed	2001–2015	-
	WorldView	Pan 0.31 m/MS 1.24 m	1–4 days	4–17	Licensed	2007–present	[79]
	Geoeye	Pan 0.41/MS 1.64 m	3 days	5	Licensed	2008–present	-
	Pleiaides	Pan 0.7 m/MS 2.8 m	Sub-daily	5	Licensed	2011–present	-
	Skysat	Pan 0.9 m/MS 2 m	Sub-daily	5	Licensed	2013–present	-

Table 1. Cont.

Radar Remote Sensing Satellites							
Satellite	Frequency	Spatial Resolution	Revisit Time Period	Polarization	Access	Data Availability	Used in Buffalo/Cattle Ecological Studies
ERS-1/ERS-2	C-band (5.3 GHz)	30 m	35 days	VV	Open-source	1991–2001	-
Radarsat 1	C-band (5.3 GHz)	50 m	24 days	HH	Open-source	1995–present	-
Radarsat 2	C-band (5.405 GHz)	25 m	24 days	VV-VH	Licensed	2007–present	-
Envisat ASAR	C-band (5.3 GHz)	12.5 m	35 days	VV	Open-source	2002–2012	-
TerraSAR-X/TanDEM-X	X-band (9.6 GHz)	5 m	11 days	HH-VV	Licensed	2007–present	-
Sentinel-1	C-band (5.405 GHz)	FR* 3.5 m/HR* 10 m and 25 m/MR* 25 m and 40 m	6 days	VV-VH	Open-source	2014–present	-
Alos PALSAR 1-2	L-band (1.27 GHz)	SP* 9 × 10 m/DP* 19 × 10 m	46–14 days	VV VH	Licensed	2006–present	-
Alos PALSAR 2				HH HV			

\* Visible Near Infrared (VNIR)/Short-wave Infrared (SWIR)/Thermal Infrared (TIR)/Atmospheric Correction Bands (ACB)/Panchromatic (Pan)/Multi-spectral (MS)/Full Resolution (FR)/High Resolution (HR)/Medium Resolution (MR)/Single Polarization (SP)/Dual Polarization (DP).

Two main categories of classification methodologies are commonly used in SRS to produce landcover maps. Supervised classification methodologies use different machine learning algorithms (maximum likelihood, neural network ensembles, random forests (RF), ...) to discriminate user-determined landcover categories [93]. For example, the RF algorithm uses a set of decision trees [94] and is now widely used [95,96], with the advantages of reliable and rapid execution in processing time of large volume of variables and data [97,98]. Such approaches require the definition of a training dataset of the different classes to be distinguished before classification. On the other hand, unsupervised classifications methodologies are more automatic processes, relying on algorithms such as K-means or Agglomerative Hierarchical to discriminate landcover categories [99]. The two types of classification methods can be applied to classify either image pixels, based on their spectral or textural values, or objects, i.e., neighboring pixels with similar spectral values aggregated into "objects" prior to the classification process. In the latter case, additional object-specific features such as shapes, context features/neighborhood relation, scale-hierarchy relation can be used to characterize and classify the objects [100]. In all cases, ground-truthing data are required for accuracy assessment.

Optical satellite images such as MODIS and Landsat (Table 1) have been used extensively for land cover classification since the 1970s and have enabled the dissemination of freely available landcover map products (Table 2) that represent major landscape features on a global scale. These products provide an initial characterization of landscape features that can be useful considering landcover preliminary assessments in a particular study area and can be easily operated by users with little SRS knowledge. The recently launched ESA-S2-LC20 product (Table 2) is one good example and can fulfil such a task despite a moderate accuracy [101]. However, as their spatial resolution and typologies are possibly not adapted to the study of ungulates habitats, 'customized' landcover maps can be produced to better reflect the landscape complexity of a particular study area [102]. Implementing optical indexes of vegetation, soil (Table 3) and water (Table 4) can also potentially enhance landcover classification results [103,104].

Despite high capacities to produce landcover maps, optical satellite images are not without limitations (e.g., lack of cloud-free periods) [105] and synthetic aperture radar (SAR) images (Figure 4 and Table 1) can provide a reliable alternative to optical satellite images. SAR sensors produce their own source of illumination and therefore can operate in almost any weather condition, day or night, and penetrate different types of vegetation cover [106,107]. They have shown good results to classify landcover in general [108], forests [109] and biomass [110] in particular and are, as a result, increasingly used. Several studies have demonstrated the complementarity of SAR and optical data and concluded that using them together provides better results than using them separately [22,111,112], especially in tropical environments where the cloud coverage often hinders the use of optical satellite images [113].

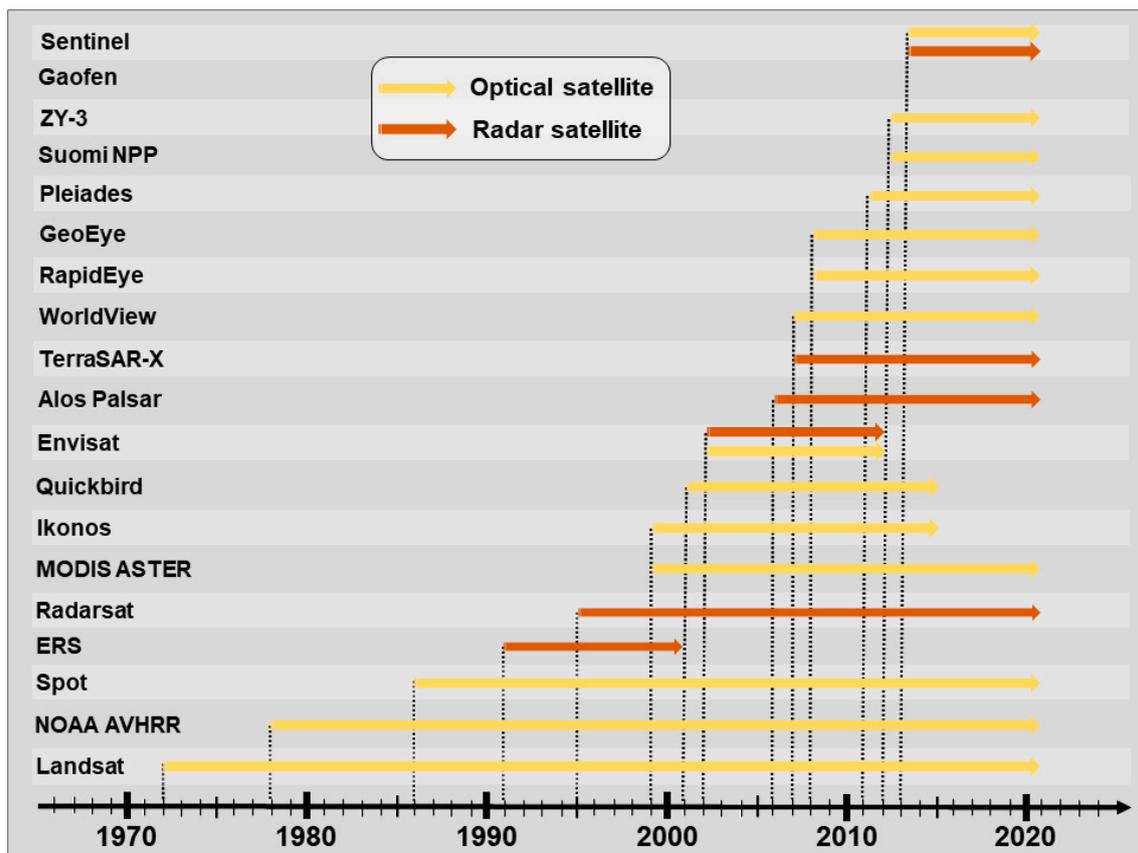
**Table 2.** List of satellite remote sensing-based landcover products.

Product Name	Spatial Resolution	Data Availability	Sensor Used	Reference
Climate Change Initiative (CCI) LandCover V2	300 m	1992 to 2015–2016–2017–2018	MERIS Full and Reduced resolution/Spot VGT	[114]
MCD12Q1 0.5 km MODIS-based Global LandCover	500 m	2001–today	MODIS	[115]
Globeland30	30 m	2000/2010	Landsat TM, ETM7, HJ-1A/b	[116]
GLC 2000	1 km	2000	SPOT 4 VEGETATION	[117]
GlobCover 2005 V2.2 2009	300 m	2005/2009	MERIS FR	[118]
GLCNMO V.1-V.2-V.3	1 km/500 m	2003/2008/2013	MODIS	[119]
GLC Share	1 km	2014	MERIS-MODIS	[120]
GLC250 m CN (2001/2010)	250 m	2001/2010	MODIS	[121]
FROM-GLC (GLC, GLC-seg, GLC-agg, GC, GLC-hierarchy)	30 m	2010	Landsat TM, ETM+	[122]
Global 30m Landsat Tree Canopy (TCC) V.4	30 m	2000, 2005, 2010, and 2015	MODIS, Landsat TM, ETM+	[123]
Global Forest Change (GFC) - GLAD (Global Land Analysis & Discovery) lab at the University of Maryland (UMD)	30 m	2000 to 2019	Landsat TM, ETM+, OLI	[80]
Copernicus Global 100 m Landcover (CGLS-LC100)	100 m	2015	PROBA-V EO and GSD	[124]
ESA-S2-LC20, 20 m (over Africa)	20 m	2016	Sentinel-2A	[125]

### 3.1.3. SRS for Detecting Landcover and Vegetation Changes

Detection of landcover changes is a complicated and integrated process and there is no optimal and applicable approach to all cases [126]. Several studies have demonstrated the capacity of Landsat images, which offer the longest continuous record of medium-resolution satellite-based earth observation (Figure 4), to monitor long term environmental changes in savanna environments [127,128]. Optical remote sensing sensors allow to monitor the evolution of the vegetation through phenology based on the spectral signature of vegetation [129,130]. For example, the widely used normalized difference vegetation index (NDVI) (Table 3) [131] was demonstrated highly correlated with the vegetation photosynthetic activity [132–134], vegetation development and seasonal patterns, forage cumulative growth period quality and quantity assessments [135–137]. These properties allow monitoring and comparing vegetation phenology through space and time at different scales. The Figure 3D, for example, represents one image (month of September 2018) of the MODIS MOD13Q1 NDVI time series, giving a spatial representation of the vegetation repartition across the HNP interface area.

NDVI was also found correlated with animal movements [138,139]. However, in savanna environments, the relevance of simple indexes such as the NDVI can be limited and must be used with caution. Using low spatial resolution satellite sensors (i.e., MODIS) or even medium resolution satellite sensors (i.e., Landsat or Sentinel-2), pixels are most of the time mixed pixels of varying proportion of trees, grasses and bare soil [140,141]. In that case, the use of soil-adjusted vegetation indexes (Table 3) may be used as complementary to enhance classification results and seasonal analyses of landcover evolution [142,143] when applied within the frame of animal movement studies.



**Figure 4.** Earth observation optical and radar satellites commissioning and time of service chronology. The length of the arrow represents the continuity and the duration of the corresponding satellite program.

### 3.1.4. SRS to Characterize Landcover and Vegetation When Studying Animal Movements in Savanna Environments

Applying landcover classification to a savanna landscape can be challenging due to sparse cover, high background soil signal, and difficulty to differentiate between spectral signals of bare soil and dry vegetation [144]. Despite these limitations, Arraut et al. (2018) produced a map of the vegetation structure of HNP in seven classes using 2013–2014 Landsat satellite images through a supervised classification process with an overall accuracy (OA) of 83.2% [102]. Figure 3B presents another example of a landcover map derived from an unsupervised classification (K-means algorithm) applied to a Sentinel-2 satellite image.

Such tailored SRS landcover maps have been used in different studies of buffalo and cattle ecology aiming at relating animal movements and landcover (Table 1). For example, Cornélis et al. (2011) used a sylvo-pastoral vegetation map derived from 30 m resolution Landsat imagery to investigate the habitat preferences of buffaloes in W Regional Park (Burkina Faso, Benin, Niger) [88]. At local scale, very high spatial resolution sensors such as Worldview-2 and IKONOS were used (Table 1) to produce fine-scale landcover maps allowing the determination of resource use of cattle in communal lands in South Africa [79] and Zimbabwe [92].

Vegetation indexes (Table 3) provide a synthetic description of the vegetation spatio-temporal dynamics and several studies have related SRS derived vegetation indices such as the NDVI or the Enhanced Vegetation Index (EVI) (Table 3) to the spatio-temporal distribution and abundance of buffalo and other ungulates species at different scales [26,29,54,68,79,86,88,89,145–147]. For example, Naidoo et al. (2012a) used MODIS EVI time series to measure the greenness of the vegetation and demonstrated the importance of this variable in explaining the variations in home range size of buffaloes in northeastern Namibia [29]. In two Australian savanna study sites, Handcock et al. (2009) showed

that the tracks of cattle from GPS collars overlaid with a NDVI map derived from a 10 m resolution SPOT-5 image, highlighting a correlation between NDVI and cattle movements [26]. Using very high spatial resolution imagery, Zengeya et al. (2015) derived a fine scale EVI map from an IKONOS image to determine the proportion of cattle home range observed inside and outside a conservation area [54].

**Table 3.** Non-exhaustive list of spectral remote sensing indexes developed to discriminate vegetation and soil from optical satellite image analysis and that can be useful within the frame of animal movement studies in savanna environments.

Spectral Index	Calculation *	Reference	Used in Buffalo/Cattle Ecological Studies
Normalized Difference Vegetation Index (NDVI)	$(NIR - RED) / (NIR + RED)$	[148,149]	[26,68,79,86,88,145–147]
Enhanced Vegetation Index (EVI)	$\frac{2.5 \times [(NIR - RED) / ((NIR + 6 \times RED - 7.5 \times BLUE) + 1)]}{[n \times (1 - 0.25 \times n) - (RED - 0.125)] / 1 - RED}$	[150]	[29,54,89,146]
Global Environmental Monitoring Index (GEMI)	$\frac{[2 \times (NIR^2 - RED^2) + 1.5 \times NIR \times 0.5 \times RED] / NIR + RED + 0.5}{n =}$	[142]	-
Soil Adjusted Vegetation Index (SAVI)	$\frac{[(1 + L) \times (NIR - RED)] / NIR + RED + L}{L = 0.5}$	[143]	-
Modified Soil Adjusted Vegetation Index (MSAVI)	$2 \times NIR + 1 - \sqrt{(2 \times NIR + 1)^2 - 8 \times (NIR - RED)}$	[151]	-
Modified Secondary Soil-Adjusted Vegetation Index (MSAVI2)	$0.5 \times [2 \times NIR + 1 - \sqrt{(2 \times NIR + 1)^2 - 8 \times (NIR - RED)}]$	[152]	-
Difference Vegetation Index (DVI)	$NIR - RED$	[153]	-
Optimized Soil-Adjusted Vegetation Index (OSAVI)	$(1 + Y \times [(NIR - RED) / (NIR + RED \times Y)])$ where $Y = 0.16$ (optimal value)	[154]	-
Soil Brightness Index (SBI)	$0.30372 \times BLUE + 0.27933 \times GREEN + 0.47434 \times RED + 0.55858 \times NIR + 0.508210 \times SWIR + 0.186312 \times MIR$	[155]	-
Two-band Enhanced Vegetation Index (EVI2)	$2.4 \times (NIR - RED) / (NIR + RED + 1)$	[156]	-
Modified Chlorophyll Absorption Ratio Index (MCARI)	$\frac{[(VNIR - RED) - 0.2 \times (VNIR - GREEN)] \times (VNIR / RED)}$	[157]	-

\* BLUE, GREEN, RED, NIR, MIR, SWIR: reflectance values in blue, green, red, near infrared, mid infrared and short-wave infrared, respectively. VNIR (visible and near infrared), SWIR1 and SWIR2: reflectance values from bands 5, 11 and 12 of Sentinel-2 respectively.

## 3.2. Surface Water

### 3.2.1. How Surface Water Distribution Influences Cattle and Buffalo Movements

The availability of surface water, artificial (e.g., solar-pumped, diesel generator) [158] or natural (e.g., dams, rivers) [159], is commonly cited to constrain movements and space-use of herbivores, including savanna buffalo [88,160–163] and cattle [164,165]. However, the influence of water sources in herbivore distributions is expected to change in response to variations in forage quality and quantity [166,167]. Buffalo are usually associated with areas close to water all-year-round and drink every day [90,168,169]. Similarly, cattle preferentially select areas close to water points, usually around their enclosures in order to optimize the ratio of energy expenditure to energy gain [79,170] and can also use boreholes which are never accessible to buffalo [90].

### 3.2.2. SRS Basics for Detecting Water and Water Dynamics

Optical SRS imagery can be efficient to discriminate water surface in different environments due to a wide range of sensors (Figure 4 & Table 1) with various spatial and temporal resolutions available [171–176]. Depending on surface water properties (i.e., size, river, pond, seasonal) to detect, different categories of sensors can be chosen [177]. However, their spatial resolution may affect their efficiency in accurately detecting surface water.

Many methodologies, from thresholding a single infrared band to the use of multi-spectral classification decision trees, have been developed to detect surface water via SRS [178–180]. They rely on the spectral signature of water, characterized by a quick reduction of reflectance from the blue to the near infrared wavelengths. Water indexes based on two or more spectral bands calculation (Table 4) and various spectral band combinations have been widely used to detect surface water [181,182] (see example in Figure 3C).

Other factors should also be considered as they potentially limit the satellite-based detection of surface water extent [183]: water depth, water turbidity variation, soil characteristics, vegetation cover, potential cloud cover and shadows. They all influence the water reflectance whatever the spatial resolution of the satellite images and influence thresholding values and the efficient use of water indexes. Despite these constraints, accurate methodologies can be developed to discriminate water by adding complementary spatial information to spectral indexes alone. Owen et al. (2015) for instance, have been able to accurately detect artificial waterholes across heterogeneous desert environments using Landsat 8 data combined with spectral indexes and texture analysis [184].

**Table 4.** Non-exhaustive list of spectral remote sensing indexes developed to discriminate water surfaces from optical satellite image analysis and that can be useful within the frame of animal movement studies in savanna environments.

Spectral Index		Calculation*	Reference
Normalized Difference Infrared Index	NDII	$(NIR - MIR) / (NIR + MIR)$	[185]
Normalized Difference Vegetation Index	NDVI	$(NIR - RED) / (NIR + RED)$	[148,149]
Enhanced Vegetation Index	EVI	$2.5 \times [(NIR - RED) / (NIR + 6 \times RED - 7.5 \times BLUE + 1)]$	[150]
Normalized Difference Water Index	NDWI	$(GREEN - NIR) / (GREEN + NIR)$	[186]
Normalized Difference Water Index (Gao)	NDWI (Gao)	$(GREEN - SWIR) / (GREEN + SWIR)$	[187]
Modified Normalized Difference Water Index	MNDWI	$(GREEN - MIR) / (GREEN + MIR)$	[188,189]
Normalized Difference Turbidity Index	NDTI	$(RED - GREEN) / (RED + GREEN)$	[188]
Normalized Difference Phytoplankton Index	NDPI	$(MIR - GREEN) / (MIR + GREEN)$	[188]
Automated Water Extraction Index	AWEInsh AWEIsh	$AWEInsh = 4 \times (GREEN - SWIR1) - (0.25 \times NIR + 2.75 \times SWIR2)$ $AWEIsh = BLUE + 2.5 \times GREEN - 1.5 \times (NIR + SWIR1) - 0.25 \times SWIR2$	[190]
Water Index	WI	$1.7204 + 171 \times GREEN + 3 \times RED - 70 \times NIR - 45 \times SWIR1 - 171 \times SWIR2$	[191]

\* BLUE, GREEN, RED, NIR, MIR, SWIR: reflectance values in blue, green, red, near infrared, mid infrared and short-wave infrared, respectively. VNIR (visible and near infrared), SWIR1 and SWIR2: reflectance values from Bands 5, 11 and 12 of Sentinel-2, respectively.

Synthetic aperture radar (SAR) satellite images can be used independently or in combination with optical satellite images in order to detect surface water [192,193]. The recent increase in number of operational SAR sensors (Table 1 & Figure 4) has favored their use for surface water detection. Indeed, several SAR-based water detection methodologies have been developed such as the surface water detection through supervised and unsupervised classifications [194,195], thresholding [196,197], object-based image analyses [198,199] and hybrid approaches [200,201]. The application of these different methodologies led to the development of several surface water products (Table 5) [202–205].

The accuracy of the SAR-based surface water detection methodologies varies. Terrain shadowing due to the topography can result in a side-looking effect [197]. The importance of the vegetation layer can produce double-bounce scattering of the signal that increases the backscatter measured in the SAR image [206]. The strong wind that roughens the water surfaces can lead to misclassification errors and the threshold value to discriminate the surface water is dependent of the image quality acquisition and the type of landscape [193]. Nevertheless, surface water long-term monitoring has been successfully implemented in a savanna environment via a multi-SAR-system at high and very-high spatial resolution [207].

### 3.2.3. SRS to Detect Surface Water When Studying Animal Movements in Savanna Environments

SRS-based water products like the Global Surface Water (GSW) and the Global Water Body map (G3WBM/G1WBM) present the advantage to have a higher spatial resolution and temporal frequency compare to the other products listed in Table 5. These products are suitable to detect massive bodies of water at a continental scale and can be of interest for preliminary analyses, however they show strong limitations when trying to discriminate localized, small or seasonal surface water which are predominant in savanna environments [208]. Indeed, detecting surface water in savanna environments via remote sensing at a landscape scale remains challenging mostly because of surface water seasonality dynamics, landscape heterogeneity and variety in surface water area sizes and morphologies [208,209].

Increasing availability of free medium-resolution optical and radar satellite sensors such as Sentinel-1 and Sentinel-2 (Table 1) offers potentialities to accurately discriminate, via supervised classification, surface water and surface water dynamics [210]. Among the different spectral remote sensing indexes developed to discriminate water surface from optical satellite images (Table 4), the MNDWI and NDWI are the most commonly used [211] and were identified as efficient discriminating indexes for the detection of surface water extent in savanna environments [177,212]. In the case of the HNP study area shown in Figure 3C, a time series of 12 Sentinel-2 images (one image per month for the year 2018) combined with the application of the RF algorithm on MNDWI and NDWI indexes (Table 4) was used to characterize the presence and seasonal dynamics of the surface water.

So far, water spectral indexes in combination with supervised classification have hardly been used in direct relation with buffalo and cattle movements, although their potential within this framework have already been stressed [212]. Recently, Naidoo et al. (2020) used the NDWI calculated from Sentinel-2 images to detect ephemeral water source in relation with buffalo and elephant movements in Namibia [91]. However, most of the reviewed studies integrating water into their analysis only used on-site observations of surface water [88,147,167] and natural or artificial waterholes [17,213–216].

**Table 5.** Non-exhaustive list of remote sensing-based water products.

Product Name	Developer	Spatial Resolution	Frequency	Data Availability	Reference
Global surface water (GSW)	EC JRC (European Commission Joint Research Center)/Google	30 m	Monthly Yearly	1984–2015 1984–2019	[217]
CCI global map of open water bodies (WBP V4.0)	ESA (European Space Agency) - climate change initiative(CCI)	300 m to 1 km	7 days–1 year	2000–2015	[218]
Global lakes and wetlands database (GLWD)	University of Kassel/World Wildlife Fund (WWF)	1 km	1 year	2004	[219]
SRTM water body data product specific guidance (SWBD)	National Aeronautics and Space Administration (NASA)	90 m	1 year	2000	[220]
SAR-Based water body indicator (SAR-WBI)	ESA	150 m to 1 km	6 to 12 days	2005–2012	[221]
MOD44W	NASA	250 m	yearly	2000–2015	[222]
Copernicus WB	Copernicus program-ESA	300 m to 1 km	10 days	2014–present	[223]
Global 3-s/1-s water body map (G3WBM/G1WBM)	Department of Integrated Climate Change Projection Research, 4 Japan Agency for Marine-Earth Science and Technology	30 m to 90 m	1 year	2018	[224]

### 3.3. Fire Regimes

#### 3.3.1. How Fire Influences Cattle and Buffalo Movements

Savanna is prone to fire due to the existence of a highly flammable continuous vegetation layer with ideal burning conditions during the dry season [225,226]. Savanna fires can thus affect herbivores movements, by impacting indirectly the quantity and quality of the grazing resources available [227] or by reducing cover to hide from predation [228]. Although most herbivores are attracted to the recently burned areas due to nutritious regrowth [229], buffalo habitat selection during the dry season appear to be strongly constrained by the occurrence of fire, probably due to a great reduction of the quantity of forage [75]. Fire can also affect the migration distance of buffalos during the wet season [146].

Movement patterns of cattle are also influenced by the occurrence of fire. In Kenyan savanna ecosystems, prescribed burning improved cattle forage intake but only in areas that cattle did not share with wildlife [230]. Savanna fires could, therefore, affect livestock-wildlife coexistence at the interfaces by altering the intensity and frequency of forage use [229].

#### 3.3.2. SRS Basics for Detecting Fire and Fire Dynamics

Optical SRS can be used to spatially and temporally detect and characterize burnt area and burn severity [231–233] based on the detection of changes in the spectral signatures of vegetation [234] with a reflection reduction in the visible and near infra-red (NIR) spectral bands. Indeed, the charring and removal of vegetation are largely visible and detectable in the infrared [235].

Various SRS-based approaches have been developed to monitor fire [236,237], including aggregate active detection [238,239], multi-temporal composites analyses [240], the use of spectral indexes [241], including vegetation indexes such as NDVI or GEMI (Table 3), spectral mixture analysis [242], machine learning classification [243,244], time series change detection [245] and hybrid approaches mixing time series change detection with machine learning classification [246,247]. If these methods provide user friendly fire products (Table 6) and helpful fire spectral indexes (Table 7) by capturing most aspects of

the spatial and temporal distribution of the fire effects, it can be difficult to relate them to actual burned area due to inadequate spatial and temporal resolutions, variability in cloud cover and differences in fire behavior [248]. Active fire detection algorithms may either: (i) underestimate the area burned in grassland and savanna ecosystems as the fire progresses rapidly across the landscape [249] and because small and low-intensity fires may not be detected [250]; (ii) overestimate the burned area for isolated fire points smaller than the pixel dimension [250]. In this instance, the MODIS fire products MOD14A2/MYD14A2 and MCD45A1 (Table 6) provide three categories of confidence (low, medium, high) of fire detection (Figure 3E), offering flexibility for a targeted use in accordance with the user's choice.

### 3.3.3. SRS to Characterize Fire when Studying Animal Movements in Savanna Environments

The Figure 3E shows an example of the MODIS fire product MOD14A2 (Table 6) at the HNP interface, illustrating the capacity of such product to depict with a 1km spatial resolution the active fire temporal and spatial dynamics and its potential for conducting seasonal- and inter-annual analyses. Despite the availability of numerous SRS-based fire products offering a wide range of applications (Table 6), according to our review only one of them has been used in relation with buffalo and cattle movement studies. Naidoo et al. (2012b) used the MODIS MOD14A2/MYD14A2 product to quantify the relative effect of dry season variables, including savanna fires, on subsequent wet season buffalo migration distance in a large study area running east-west between the northeast corner of Namibia, Angola and Botswana [146].

As shown by this example, and despite limitations, the data listed in Table 6 presents the advantage to describe fire phenomenon in relation with animal distribution and movement in regions with scarce fire information [251]. In well-documented areas, these data can potentially be used to complement existing fire databases. Combining better spatial resolution from new sensors such as Sentinel-3 (Table 1) and remote sensing-based fire products with designed spectral indexes to detect fire (Table 7) is promising. It could potentially reduce errors and uncertainties in satellite-derived fire dates and ignitions, and improve coverage of small fires. The recently launched FireCCI50 product (Table 6) offers an increased spatial resolution (250 m) and a better burned area estimation compared to the MODIS fire products [249]. This spatial resolution could be useful when aiming to integrate fire assessment in animal movement study at the landscape scale in savanna environments.

**Table 6.** Non-exhaustive list of satellite remote sensing-based fire products.

Product Name	Spatial Resolution	Orbital Frequency	Data Availability	Reference	Use in Ungulates Ecological Studies
MOD14A2/MYD14A2	1 km	Every 8 days	2000–present	[252]	[29]
MCD45A1	500 m	Monthly	2000–present	[253]	-
MCD64A1	500 m	Monthly	2000–present	[248]	-
VIIRS 750 m active fire (VNP14)	750 m	twice/day (IR and day/night VIS/NIR channel) once/day (VIS)	2011–present	[254]	-
VIIRS 375 m Active Fire (VNP14IMG)	375 m	twice/day (IR and day/night VIS/NIR channel) once/day (VIS)	2016–present	[238]	-
Sentinel-3 SLSTR (level-2 FRP product)	1 km	Daily	2018–present	[255]	-
AVHRR Fire Detects from the Fire Identification, Mapping and Monitoring Algorithm (FIMMA)	1 km	Daily	1978–present	[256]	-
ESA FIRE_CCI	300 m	Monthly	2016–present	[257]	-
FireCCI51	250 m	Monthly	2001–2019	[258]	-

**Table 7.** Non-exhaustive list of spectral remote sensing indexes developed to discriminate fire from optical satellite image analysis and that can be useful within the frame of animal movement studies in savanna environments.

Spectral Index	Calculation *	Reference
Normalized Burned Ratio (NBR)	$(NIR - SWIR) / (NIR + SWIR)$	[258]
Burned Area Index (BAI)	$1 / (NIR - 0.06)^2 + (RED - 0.1)^2$	[259]
Mid Infrared Burned Index (MIRBI)	$10 \times SWIR + 9.8 \times SWIR + 2$	[260]
Char Soil Index (CSI)	$NIR / SWIR$	[261]
Normalized Burn Ratio Thermal (NBRT)	$(NIR - SWIR \times TIR) / (NIR + SWIR \times TIR)$	[262]
Normalized difference Vegetation Index Thermal (NDVIT)	$(NIR - RED \times TIR) / (NIR + RED \times TIR)$	[262,263]

\* RED, NIR, MIR, SWIR, TIR: reflectance values in red, Near Infrared, Mid Infrared, Short-wave Infrared and Thermal Infrared, respectively.

### 3.4. Precipitation

#### 3.4.1. How Precipitation Influence Cattle and Buffalo Movements

In southern African savannas, the availability in time and space of natural resources (i.e., surface water and forage) is strongly dependent of the precipitation seasonal variations [88,264]. Most precipitation occurs during the wet season (November to April). However, the spatio-temporal distribution of precipitations in southern Africa is highly heterogeneous at medium-scale inducing specific movement patterns such as nomadism [265]. During the dry season (May to October), precipitation are lower or nonexistent, and the availability of natural resources decreases. This high heterogeneity in rainfalls dictates the behavior of wildlife [8].

Buffalos, like other ungulates of semi-arid savannas, are able to track precipitation events over large distances [88]. Buffalos living in wetter areas, such as in forested savanna habitats, tend to maintain smaller and constant home ranges than those in drier open savanna habitats [160,266]. In these more arid areas, natural resources are spatially unevenly distributed, forcing buffalos to travel longer distances in their search for forage and water [29,146,162]. In some areas however, smaller buffalo home ranges have been noticed during the dry season compared to the wet season [266–268].

Precipitation also affect cattle movement patterns through the combined influence on their grazing behaviors and the spatial grazing constraints imposed by livestock owners [269]. For example, cattle around Kruger National Park, South Africa, select forage with higher quantity and quality during the dry season but behave more like non-selective bulk grazers during the wet season, directly influencing their daily traveled distance [79].

#### 3.4.2. SRS Basics for Measuring Precipitation

Satellite-based precipitation measurements with advanced infrared (IR), passive microwave (MW) and radar (SAR) sensors provide a complementary alternative to in-situ records [62,270] as they give a full spatial and temporal coverage with a good accuracy (Table 8) [271–278]. Yet, despite the growing collection of satellite-based rainfall measurement datasets providing near-real-time estimates [63], only a few high-resolution satellite-based products providing historical data at the daily time-step with real-time or near-real-time updates for the African continent are publicly available (Table 8). To improve the accuracy of rainfall estimations, the merging of satellite and gauge measurements have been designed, thus maximizing the benefits of each data type [279,280]. Noticeable differences can be found in the performance of the satellite precipitation estimates though [281]. Satellite-based precipitation products generally overestimate precipitation events under 200 mm/month and tend to underestimate daily time scale precipitation events compare to the decadal and monthly time scale

precipitation events [272,282,283]. However, the main precipitation regimes and the spatial patterns of mean annual precipitation are well reproduced [281,284].

Satellite-based precipitation measurements have the advantage of providing full spatial coverage compared to the more accurate but spatially limited rain gauge data [285]. Furthermore, observational precipitation measurements over Africa include uncertainties that can bias analysis [286,287]. The TMPA 3B42 V7 (TRMM) offers the advantage of consistency at the daily time-scale [281]. It is a performing product for depicting inter-annual variations but offers a coarser spatial resolution (Table 8) which could be detrimental when studying animal movement at the landscape scale. Since 2019, the GPM IMERG v06 algorithm fuses the early precipitation estimates collected during the operation of the TRMM satellite (2000–2015) with more recent precipitation estimates collected during operation of the GPM satellite (2014–present). Therefore, the GPM IMERG v06 now offers 20 years of data coverage and can potentially be of interest regarding animal movement studies at the landscape scale regarding its spatial resolution of 0.1° and its broad coverage (Table 8).

The products that combine thermal infrared and passive microwave imagery such as RFE or CHIRPS (Table 8), perform comparatively well and outperform products which are only based on thermal infrared imagery such as TARCAT (Table 8) [272]. They could be used in complement or independently with higher spatial resolution satellite-based precipitation products such as the GPM product (Table 8) to reliably assess precipitation at the landscape scale in seasonal-prone environments such as African savannas when lacking in-situ precipitation data.

**Table 8.** Non-exhaustive list of available satellite-based precipitation products.

Product Name	Temporal Resolution	Spatial Resolution	Data Availability	Coverage	In-Situ Calibration	Reference	Use in Ungulates Ecological Studies
TRMM (TMPA 3B42 V7)	3 h	0.25°	1998–Mid 2019	50°S–50°N	yes	[288]	[29,146]
TRMM (TMPA 3B43 V7)	Monthly	0.25°	1998–Mid 2019	50°S–50°N	yes	[288]	[29,146]
PERSIANN-CDR	Hourly/Daily/Monthly/yearly	0.25°	1983–present	60°S–60°N	no	[289]	-
GPCP (1dd)	Daily	1°	1996–present	90°S–90°N	no	[290]	-
GPCP V2.3	Monthly	2.5°	1979–present	90°S–90°N	no	[291]	-
CPC Global	Daily	0.5°	1979–present	90°S–90°N	yes	[292]	-
CMAP	Monthly	2.5°	1979–present	90°S–90°N	yes	[293]	-
Cmorph	30 min	0.25°	2002–2017	60°S–60°N	no	[294]	-
GPM (IMERG V06)	30 min/3 h/Daily	0.1°	2000–present	60°S–60°N	no	[295]	-
MSWEP V2	3 h/Daily	0.1°/0.5°	1979–2017	90°S–90°N	yes	[296]	-
SM2RAIN-ASCAT	Daily	0.5°	2007–2018	60°S–60°N	no	[297]	-
TAMSAT V3.1	Daily	0.0375°	1983–present	38°025N–35°9625S 19°0125W–51°975E	yes	[62,63]	-
CHIRPS v2p0	Daily	0.05°	1981–present	50°S–50°N	yes	[298]	-
ARC V.2	Daily	0.1°	1983–present	40°S–40°N	yes	[299]	-
RFE 2.0	Daily	0.1°	2001–present	40°S–40°N 20°W–55°E	yes	[300]	-
EPSAT-SG	15 min	0.0375°	2004–present	African continent	yes	[301]	-
MPE	15 min	0.0375°	2007–present	African & European continents	no	[302]	-

### 3.4.3. SRS to Measure Precipitation when Studying Animal Movements in Savanna Environments

Only the National Oceanic Atmospheric Administration (NOAA) African Rainfall Climatology (ARC V.2), the Climate Hazards Group InfraRed Precipitation with Station data version 2.0 (CHIRPS20) and the Tropical Applications of Meteorology using SATellite data and ground-based observations (TAMSAT V3.1) provide continually updated daily time-step data [63,303]. Therefore, due to their

spatial and temporal resolutions (Table 8) they are potentially suitable for applications in animal movement studies in African savanna environments. Figure 3F shows a spatial representation of the TAMSAT V3.1 at the HNP interface while demonstrating the product capabilities to detect spatially contrasted precipitation within a relative extensive area (1192 km<sup>2</sup>). TAMSAT V3.1 (Table 8) is among the best product in terms of precipitation event detection at a spatial resolution of 0.0375° [304] but it may underestimate monthly rainfall measurements [284].

Despite the availability of these precipitation satellite-based products, the most commonly method to characterize precipitation in relation with animal movement and distribution remains the use of in-situ gauging stations data [170,305]. Only few studies have used satellite-derived precipitation data in relation with buffalo movements. Naidoo et al. (2012a, 2012b) used TRMM data (Table 8) to characterize which environmental factors, including precipitation, explain buffalo migration patterns [146], and variation in buffalo home range sizes in northeastern Namibia [29].

#### 4. Discussion

The literature on the current knowledge on buffalo and cattle movements and their interactions was here linked to an inventory of available and relevant SRS tools to characterize the environmental drivers of these movements, found in savanna type landscape environment.

Landcover, surface water, savanna fire and precipitation emerged through this review as environmental drivers defining buffalo and cattle movements at the edge of protected areas in Africa and in southern Africa in particular. Optical and radar SRS are both currently operational to characterize these drivers and have already been used independently for several ecological applications, including animal movements [19,25,306] but have never been collectively linked in animal movement studies. The need of dynamic environmental products to analyze animal movement requires that the increasing number of SRS sensors, the multiple tools and the large quantity of data available become more accessible and easy to use to movement ecologists [307].

##### 4.1. General Observations

Faced with an overabundance of available data, one should gain insight on data quality and the methods, algorithms and applications of using data in animal movement studies. SRS data must often be combined with in-situ measurements, which are sometimes not available, for validation purposes and accurately representation of environmental drivers. SRS has to be considered only as a partial view of the terrain and remain imperfect by definition [308]. Furthermore, the use of SRS products may be limited by the time-span of their availability, their spatial and temporal resolution and coverage, their spectral characteristics (Table 1). The revisit time period of a SRS product (Table 1) does not mean that it will be usable at the same frequency, as the quality of the image may not always be optimal at each acquisition (e.g., cloud cover, limited spatial extent that doesn't cover the desired area, ... ).

These limitations often imply a trade-off between spatial and temporal resolutions [309] and/or between spatial resolution and spatial extent coverage [310]. For instance, high and very-high spatial resolution images are not necessarily appropriate for all research questions as they contain large amounts of data, heterogeneity of spectral values and diversity of objects in small spatial extents that can significantly complicate methodology applications [310]. Data pre-processing for a SRS derived application is not only costly in processing time and in expertise but also in financial resources. Naidoo et al. (2012a) estimated that weekly acquisition of very high resolution Quickbird imagery (Table 1) to detect small ephemeral water sources within the frame of their study in relation with buffalo movements would have cost close to USD \$9 million [29]. One has to be aware of the computing capacities available, the allowed time and the appropriate algorithm for the completion of SRS analyses [34,311].

##### 4.2. Landcover and Vegetation Characterization

Our review showed that the use of SRS to understand cattle or buffalo movement ecology mainly benefited from open-access products and standard image processing methods. EVI and NDVI are

widely used vegetation indexes to characterize vegetation availability and evolution patterns in these studies [26,29,54,88,312]. However, other spectral indexes such as the Soil Adjusted Vegetation Index (SAVI) (Table 3) that eliminate soil-induced variations in vegetation indexes [143] have not been used at all in existing buffalo and cattle movement studies. The use of such spectral indexes could complement more classic vegetation indexes by overcoming certain associated limitations when characterizing savanna landscapes through SRS approaches (i.e., mixed pixels) [143,313,314].

Few studies listed in this review use high or very high-spatial resolution satellite images to characterize the landcover [54,79,89] comparatively to the studies that use medium or low-spatial resolution satellite images such as MODIS (Table 1) to derive spectral indexes [86,87,135] and Landsat or Spot (Table 1) to characterize landcover [11,70,88,90]. Indeed, high spatial resolution imagery is not necessarily appropriate for all research questions, especially because its limited spatial extent requires the acquisition of several images to cover large areas at a high financial cost [315]. High and very high spatial resolution images contain large amounts of data, heterogeneity of spectral values and diversity of objects that significantly complicate methodology applications such as landcover classification [310]. However, since 2015, open-source Sentinel-2 images (Table 1) bring a spatial resolution and a temporal continuity gain compared to other medium spatial resolution images that could potentially improve spectral indexes or landcover derivation over large areas while maintaining relevance in application for landscape scale analysis.

As the human and livestock populations grow in Africa [2,316], the pressure on protected areas' boundaries increases resulting in the transformation of natural landscapes and the creation of hard edges between protected areas and their surroundings by human infrastructures and activities (e.g., buildings, roads, cleaned land for cultivation, pasture, trees and grasses harvest) [68]. These two factors combined directly impact the movement of buffalo and cattle as they cross the natural park borders to find foraging or water resources. Human infrastructures including fences, human settlements and agricultural areas also represent potential barriers to animal movement. For example, movement rates of buffalos living near fences appear to be low [317] and large migratory movements are limited by fences [146] when they are not damaged by elephants [6]. SRS can play a fundamental role to characterize the human factors (infrastructures, activities) into the buffalo and cattle movement processes. For instance, crops can potentially provide an important resource for both buffalo and cattle during the wet season in southern African savanna even if both species are prevented to enter fields with growing crops (e.g., using different practices such as wildlife deterrent measures and livestock herding). Time series SRS derived vegetation indexes such as EVI or NDVI (Table 3) have been efficiently used as phenology indicators [318,319] combined with landcover classification [320], high-resolution optical and radar sensors [321] for crop and pasture monitoring and space delimitation. Concerning hardly distinguishable objects from space such as fences, human settlements and roads, the increasing availability of very high-resolution (Worldview-2, Pleiades, . . . ) satellite images (Table 1) offer a wide range of possibilities to characterize these landscape features via landcover object-based approach classification [23]. These methodologies could certainly be used independently or combined, bringing a wide range of indicators for animal movement and interactions analysis.

#### 4.3. Surface Water Delineation

Several methods such as spectral indexes thresholding (Table 4), image classification, surface water spatial delineation through satellite image textures [184], have been efficiently used independently to map surface water bodies. However, the numerous remote sensing-based water products presented in Table 5 have not been used in the different buffalo and cattle movement reviewed studies. Similarly, water spectral indexes listed in Table 4 and SAR images (Table 1), with the exception of one study that used NDWI derived from Sentinel-2 images in relation with buffalo movements [91], have not been used despite their potential to improve classification algorithms and water detection in savanna environments [177,203,204,207,212]. This may partly result from a lack of knowledge about the

existence and availability of SRS products in the movement ecology community, a major gap that this review aims to fill.

According to our review, the use of SRS offers a potential that remains to be explored regarding the detection of surface water at a landscape scale in savanna environments, as a driver of wild and domestic ungulates movements. Indeed, classification of surface water derived from optical and/or radar medium spatial resolution images (Table 1), could provide spatially delineated surface water areas and water resource seasonal variations at a landscape scale and on a monthly basis (Figure 3B), which constitutes a clear advantage in term of spatial representation over in-situ fixed referenced points.

#### 4.4. Savanna Fire Characterization

SRS plays an important role in determining the spatial extent and timing of fires in savanna environments [244,322]. However,, few of the reviewed studies focusing on buffalo and cattle movements used satellite remote sensing-based fire products (Table 6) and none of them used designed optical images derived fire spectral indexes (Table 7) despite their proven efficiency [323]. Landsat and, increasingly, Sentinel-2 (Table 1) for example, are extensively used for medium spatial resolution fire scar mapping in savanna [250,324] and could provide potential improved results for studies that use lower spatial resolution images [146].

However, mapping fire severity is more challenging than just mapping the occurrence of fire. One major limitation of all optical SRS approaches is the presence of cloud cover that hinders the temporal continuity of the follow-up [325]. For animal movements studies, the severity of a given fire event is more relevant than its frequency and timing alone. To bypass such limitation, SAR images could be used. Philipp and Levick (2020), for example, demonstrated that C-band SAR data can contribute to effectively map fire severity in tropical savanna [325]. Characterizing savanna fire severity in addition of being able to locate fire events could also be useful for measuring more accurately the influence of human land use practices [326] and how it potentially affects animal movements.

#### 4.5. SRS for Precipitation Characterization

According to our review, only the TRMM product (Table 8) have been used for buffalo and cattle movement studies [29,146]. This is probably because most of the satellite-based precipitation products are difficult to apprehend for non-specialists, thus compromising their potential use in animal movement studies. They usually present unconventional output file formats, non-standardised precipitation measurement units and uncommon map projection systems. Therefore, potential users need to access metadata that are most of the time difficult for non-SRS specialist to understand in order to assess satellite-based precipitation products usefulness. The mitigation of this constraint by simplifying the use of satellite-based precipitation products could be greatly beneficial for animal movement studies.

The use of satellite-based precipitation products combined with in-situ precipitation data when available remains paramount for more accurate estimations of precipitation trends at a local scale [272]. Additionally, algorithm performances of satellite-based precipitation products (Table 8) greatly vary depending on location, topography, local climate, and season [273,282,283]. This performance variability needs to be taken into account before choosing a satellite-based precipitation product for a specific application and in accordance with the study area geographical specifications.

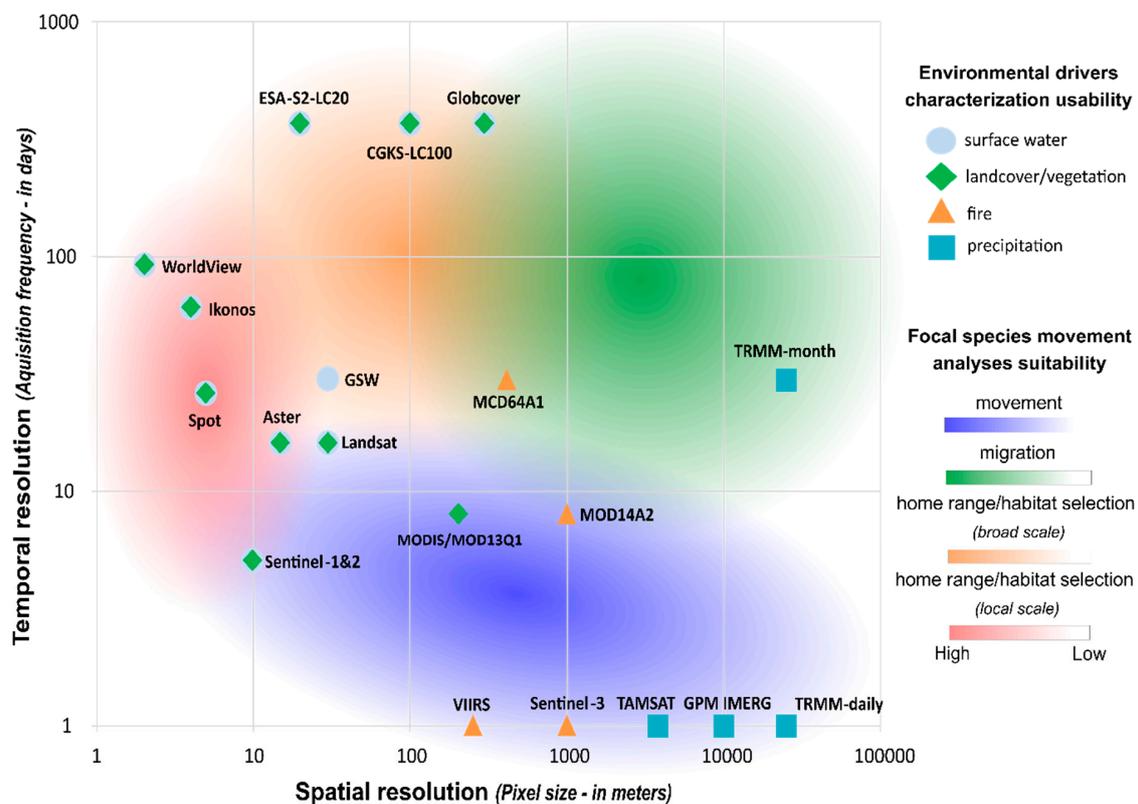
#### 4.6. Selection of Suitable SRS Products to Study Buffalo and Cattle Movements in Southern Africa

Choosing a set of SRS tools for the characterisation of environmental drivers influencing the buffalo and cattle movements is firstly driven by the question to be addressed (e.g., habitat selection, landscape scale movement patterns, long-distance migration, . . . ), which in turn defines the spatiotemporal scales to be considered [59]. Additional criteria such as the required SRS expertise, computing resources, and cost, may be taken into account too (see Section 4.1). Figure 5 provides an illustration of suitable

SRS products for ecologists to characterize environmental drivers impacting animal movements in southern Africa according to their temporal and spatial resolution scales.

High and very high spatial resolution sensors can be used to provide fine-grain maps of landcover and water surface for habitat occupation and habitat selection studies at local scale. Very high spatial resolution images such as Worldview 2, Pleiades, or Ikonos images can be used to discriminate small objects within the landscape (i.e., fences, human settlements, road networks) and characterize landscape at fine scale (ideal for the study of small animal species with a small home range). However, they are costly and require remote sensing expertise and high computing power.

These fine-scale landcover maps can be combined with precipitation and savanna fires data at coarse spatial resolution but with a high temporal repetitivity for studies that focus on daily animal movements. For instance, precipitation TAMSAT 3.0 (Table 8) product is easily accessible and covers the entire African continent at 4.8 km of spatial resolution with daily, pentadal, decadal, monthly and seasonal temporal resolutions; recent VIIRS active fire images (Table 6) offer improved spatial and temporal resolutions compared to former fire products. These products are easy to use and do not require high computing power.



**Figure 5.** Suitable SRS products for ecologists to characterize environmental drivers impacting animal movements in semi-arid savannas landscapes. These SRS products are represented according to their temporal (ordinate axis) and spatial resolution scales (abscissa axis) and can be used for different type of analyses related to animal movements (movement patterns, home-range and habitat selection at broad and local scales, migration) [59]. We define the “movement” (represented in blue) as the motion initiated by a variety of methods that focal species use to move from one place to another. The “migration” (represented in green) is defined as long distance movements to a different environment involving periodical and cyclical dynamics in space and time. Home range and habitat selection (represented in orange at broad scale and in red at local scale) are considered as areas where focal species regularly move depending on natural resource selections and social interactions and behaviors. Note that the contours of the different analyses categories are blurred to emphasize the fact that there are no clearly established boundaries between these categories.

For studies focusing on animal movements at a coarser spatial and temporal scales, landcover and vegetation (Table 2), fire (Table 6) and water (Table 5) free products can be used for preliminary assessments in areas where in-situ data are difficult to collect or nonexistent. These products are easily accessible online, easy to use for non-SRS specialists, well documented and require little computing power in order to cover large areas. In addition, they can be efficiently combined with higher spatial resolution and custom made SRS products.

## 5. Conclusions

SRS extends the analytical capacity of ecologists in many fields including animal movement studies [20]. New SRS sensors are continuously launched thus expanding and increasing the potential applications of these tools (Figures 4 and 5). The Committee on Earth Observation Satellites (CEOS) reports that its member agencies are currently operating or planning more than 300 different satellite Earth observation missions by 2030, carrying over 900 different measurement instruments offering different spatial resolutions and spectral capabilities [327]. Medium-resolution Sentinel-1 and Sentinel-2 images (Table 1) are particularly promising in the field of animal movement as they provide continuous open-source data since 2014–2015 at a 10 m spatial resolution with radar and optical sensors. However, given the SRS sensors and applications diversity, it is paramount to determine which SRS product is best suited for a given scale of analyses and how potential inherent limitations can affect the latter.

To facilitate the use of SRS products in ecological movement research studies, a better data accessibility such as the European Spatial Agency Sentinel program, which promotes open data, and training platforms to familiarize users with the utilization and the potentialities of SRS data, are needed. The collaboration of movement ecologists with remote sensing experts within a multi-disciplinary approach could also help to integrate more efficiently remote sensing products in ecological movement research.

**Supplementary Materials:** The open-source data and developed products presented in Figure 3 are listed below: TAMSAT v3.0 data: the entire archive is available in direct download via batch process at <https://www.tamsat.org.uk/data/archive> with the script detailed at [https://www.tamsat.org.uk/public\\_data/public\\_scripts/wget\\_TAMSATv3.0](https://www.tamsat.org.uk/public_data/public_scripts/wget_TAMSATv3.0); The MOD/MYD14A2 (MODIS thermal anomaly product) data are available to download at <https://search.earthdata.nasa.gov/search> after login—Archived by National Aeronautics and Space Administration, U.S. Government, LP DAAC. <https://doi.org/10.5067/MODIS/MOD11A2.006>; The MOD/MYD13Q1 (MODIS vegetation product) data are available to download at <https://search.earthdata.nasa.gov/search> after login—Archived by National Aeronautics and Space Administration, U.S. Government, LP DAAC. <https://doi.org/10.5067/MODIS/MOD13Q1.006>; The Sentinel-2 images are freely available at <https://scihub.copernicus.eu/dhus/#/home> after login. The land cover map is available to download at CIRAD depository website: Rumiano, Florent; Miguel, Eve; Valls-Fox, Hugo; Chamailé-Jammes, Simon; Caron, Alexandre; Tran, Annelise, 2020, “Land cover map, Dete site, Hwangue National Park, Zimbabwe”, doi:10.18167/DVN1/BJJZJV, CIRAD Dataverse, V1; The surface water map is available to download at CIRAD depository website: Rumiano, Florent; Miguel, Eve; Valls-Fox, Hugo; Chamailé-Jammes, Simon; Caron, Alexandre; Tran, Annelise, 2020, “Monthly surface water maps, Hwangue National Park, Zimbabwe, 2018”, doi:10.18167/DVN1/KPSYME, CIRAD Dataverse, V1, The buffalo and cattle GPS data access are subject to authors’ authorization.

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