

Supplemental Materials

Suppl. Table S1: Recent research studies related to development of early warning metrics of drought-induced stress and mortality in forests using remote sensing-based data

Variable	Data / EO Data	Forest type	Study Area	Citation
Microwave Temperature–Vegetation Drought Index (MTVDI)	Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E)/Aqua ascending daily global 0.25-degree terabyte data, MODIS data	Tropical evergreen forest	Amazon basin	Liu et al., 2021
Forest Drought Response Index (ForDRI)	MODIS	More than 80 tree species, dominated by Oak/Hickory, Loblolly/Shortleaf pine, and Maple/Beech/Birch type groups.	Eastern U.S.	Tadesse et al., 2020
GNDVI, NDVI and NIRv	Vegetation indices NDVI, GNDVI and NIRv detected by NIR-camera	Quercus species: <i>Q. robur</i> L., <i>Q. pubescens</i> Willd., and <i>Q. ilex</i> L.	Nursery greenhouse, Pistoia, Italy	Raddi et al., 2021
NPV	Landsat TM and ETM+	Aspen Forest	San Juan National Forest, Western Colorado, USA	Anderegg et al., 2019a
NDVI	NOAA AVHRR - GIMMS data	Conifer forest, deciduous forest, mixed coniferous and deciduous forest and tundra	Boreal North America	Goetz et al., 2005
NDVI	AVHRR - GIMMS, SPOT-VGT and MODIS	Multiple vegetation types	Tibetan Plateau, China	Liu et al., 2019
NDVI	MODIS	Multiple species	State of Texas, USA	Moore et al., 2016
NDVI	AVHRR, MODIS and Landsat	White spruce, Alaska birch, Quaking aspen, Black spruce	Central-western boreal North America	Rogers et al., 2018
NDVI	Aerial Imagery - FireMapper 2.0, thermal-imaging radiometer and 2 Kodak MegaPlus 1.6i digital cameras mounted aboard a King Air A100 aircraft.	Jeffrey pines	Southern Sierra Nevada	Gulke et al., 2020
NDVI, EVI, NDWI	MODIS	Oak-woodlands, chaparral, and conifers, mixed conifer forests	Southern and central Sierra Nevada region, USA	Byer and Yufang, 2017

		with many species of pines and firs		
NDVI, EVI and Normalized Difference Infrared Index (NDII)	ADS40 and MODIS	<i>Pinus radiata</i> plantation	Green Hills State Forest, New South Wales, Australia	Verbesselt et al., 2009
Elevation, Slope	Demographic data and climatic data from Parameter-elevation Regression on Independent Slopes Model (PRISM)	Temperate coniferous forests - several different forest types, including ponderosa pine-mixed conifer, white fir, mixed conifer, red fir, Jeffrey pine and subalpine forests	Sequoia and Yosemite national parks, Sierra Nevada, California	Van Mantgem and Stephenson, 2007
Relative Water Content (RWC)	Aerial Detection and Monitoring Program data, Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E) Radiometer 2 (AMSR-2) data.	Mixed conifers, western oak and pines	California, USA	Rao et al., 2019
Canopy Water Content (CWC), NDVI	High-fidelity imaging spectroscopy (HiFIS), Landsat and LiDAR data	Conifers	Sierra Nevada mountains, California	Brodrick and Asner., 2017
Multiple vegetation and water indices	Landsat, MODIS and NAIP (National Agriculture Imagery Program) orthophotos	Ashe juniper, plateau live oak, post oak, cedar elm and honey mesquite	Edwards Plateau and Llano Uplift regions of central Texas	Schwantes et al., 2016

Suppl. Table S2. List of available UAV-compatible hyperspectral sensors and their specifications (BaySpec Inc., 2015; Cubert GmbH 2017; Fisher 2013a, b; MosaicMill Ltd 2017; Norsk Elektro Optikk AS ; Photonfocus ; Resonon Inc ; Specim ; Specim ; Ximea 2018a, b)

Manufacturer	Sensor	Spectral Range (nm)	No. of Bands	Spectral Resolution (nm)	Spatial Pixels	Acquisition Mode ^a	Weight (g)
BaySpec	OCI-UAV-1000	600-1000	100	< 5 ^b	2048 ^d	P	630 ^e
	OCI-UAV-2000	600-1000	20-25	12 to 15 ^b	400 x 200	S	6310 ^e
	OCI-D2000	475-975	40	12 to 15	500 x 250	S	540 ^f
Brandywine Photonics	CHAI S-640	825-2125	260	5 ^c	640 x 512	P	5000
	CHAI V-640	350-1080	256	2.5, 5, 10 ^c	640 x 512	P	480
Cubert GmbH	S 185 - FirefIEYE SE	450-950	125	4 ^c	50 x 50	S	490
	S 485 - FirefIEYE XL	355-750; 550-1000; 450-950	125	4.5 ^c	70 x 70	S	1200
	Q 285 - FirefIEYE QE	450-950	125	4 ^c	50 x 50	S	3000
Headwall Photonics Inc.	Micro-Hyperspec VNIR A Series	400-1000	325	5.8	1004	P	700 ^g
	Micro-Hyperspec VNIR E Series	400-1000	369	5.8	1600	P	1400 ^g
	Micro-Hyperspec NIR R640	900-1700	134	10	640	P	900 ^g
	Micro-Hyperspec NIR R320	900-1700	67	10	320	P	900 ^g
	Micro-Hyperspec Ext VNIR R640	600-1700	267	5.5	640	P	900 ^g
	Micro-Hyperspec SWIR M384	900-2500	166	10	384	P	2000 ^g
	Micro-Hyperspec SWIR M640	900-2500	267	8	640	P	1600 ^g
	Nano-Hyperspec	400-1000	270	6	640	P	<520 ^g
	Hyperspec VNIR A Series	380-1000	837	2.5 ^b	1004	P	2800
	Hyperspec VNIR E Series	380-1000	923	2.5 ^b	1600	P	3900
	Hyperspec VNIR N Series	380-1000	775	2.5 ^b	1004	P	3700
	Hyperspec UV-VIS	250-500	961	1.4 ^b	1392	P	3200
	Hyperspec SWIR	900-2500	267	6.3 ^b	384	P	4400
	Hyperspec Co-Registered VNIR-SWIR ^h	400-2500	384 (VNIR), 166 (SWIR)	5 (VNIR), 10 (SWIR)	1600 (VNIR), 384 (SWIR)	P	11300
HySpex	VNIR-1024	400-1000	108	5.4 ^c	1024	P	4200
	VNIR-1800	400-1000	182	3.26 ^c	1800	P	5000
	SWIR-384	1000-2500	288	5.45 ^c	384	P	5700
	Mjolnir V-1240	400-1000	200	3 ^c	1240	P	4000
	Mjolnir S-620	970-2500	300	5.1 ^c	620	P	4500
MosaicMill	Rikola	500-900 ⁱ	50 ^j	10 ^b	1010 x 1010	S	720 ^k
PhotonFocus	MV0-D2048x1088-C01-HS02-160-G2	600 to 975	25	15 ^b	2048 x 1088	S	75
	MV0-D2048x1088-C01-HS03-160-G2	470 to 630	16	15 ^b	2048 x 1088	S	75
	MV1-D2048x1088-HS01-G2	600 to 1000	100	10-12 ^b	2048 x 1088	P	265
	MV1-D2048x1088-HS02-G2	600 to 975	25	15 ^b	2048 x 1088	S	265
	MV1-D2048x1088-HS03-G2	470 to 630	16	15 ^b	2048 x 1088	S	265
	MV1-D2048x1088-HS05-G2	470 to 900	150	10-12 ^b	2049 x 1088	P	265
Resonon	Pika NUV	350-800	196	2.3 ^b	1600	P	2100
	Pika L	400-1000	281	2.1 ^b	900	P	600
	Pika XC2	400-1000	447	1.3 ^b	1600	P	2200
	Pika NIR-320	900-1700	164	4.9 ^b	320	P	2700
	Pika NIR-640	900-1700	328	2.5 ^b	640	P	2700

SPECIM	SPECIM FX10	400-1000	224	5.5 ^b	1024	P	1260
	SPECIM FX17	900-1700	224	8 ^b	640	P	1560
	AISA FENIX ^h	380-970	348	3.5	384	P	<15000
		970-2500	274	12	384		
	AISA FENIX 1K ^h	380-970	348	4.5	1024	P	22500
		970-2500	256	14	1024		
	AISA KESTREL 10	400-1000	-	1.75 ^c	2 040	P	4750
	AISA KESTREL 16	600-1640	-	2.75 ^c	640	P	5000
Ximea	MQ022HG-IM-LS100-NIR	600-975	100+	4	2048 x 8	P	32
	MQ022HG-IM-LS150-VISNIR	470-900	150+	3	2048 x 5	P	32

Note: ^a P – pushbroom, S – snapshot; ^b at FWHM; ^c by sampling; ^d Pushbroom length line (the other dimension depends on sweep distance); ^e with onboard computer; ^f with lens; ^g without lens; ^h suitable for medium-sized UAVs; ⁱ other ranges: 400-700, 450-800, 550-950; ^j 380 in the laboratory; ^k without battery, GPS and irradiance sensor

Suppl. Table S3. List of other available airborne hyperspectral sensors and their specifications (ASI 2018; BaySpec Inc. 2015; ESA 2018; ITRES Research Limited 2010a, b, 2012, 2014). This table provides an overview without claiming to be exhaustive.

Owner/ Developer/ Manufacturer	Sensor	Spectral Range (nm)	No. of Bands	Spectral Resolution (nm)	Spatial Resolution (m)	Spatial pixels	Weight (kg)	Scanning Mechanism ^a
NASA/JPL	AVIRIS (Airborne Visible/Infrared Imaging Spectrometer)	360 - 670 660 - 1280 1260 - 1880 1880 - 2500	32 64 64 64	9.5-10 ^b	20 ^e	677	340	W
ESA and Swiss-Belgian Consortium	APEX (Airborne PRISM Experiment)	380-970 (VNIR) 940-2500 (SWIR)	114 (VNIR) ^d 199 (SWIR)	0.6-6.3 (VNIR), 13.5-7 (SWIR) ^b	-	1024	-	P
NASA/JPL and NASA/IIP	HyTES (Hyperspectral Thermal Emission Spectrometer)	7500-12000	256	17.6 ^c	36.4 ^e	512	12 ^f	P
ITRES	CASI1500h	380-1050	288	<3.5 ^b	0.3-1.5 ^g	1500	51 ^h	P
	SASI1000A	950-2450	200	7.5 ^b	0.5-2 ^g	1000	51 ^h	P
	MASI600	3000-5000	64	32 ^b	1-3.5 ^g	600	-	P
	TASI600	8000-11500	32	110 ^c	1-3.5 ^g	600	66 ^h	P

Note: ^a W – whiskbroom, P – pushbroom; ^b at FWHM; ^c by sampling; ^d can be extended up to 334 depending on binning; ^e at 20 km altitude; ^f does not include 1 rack of electronics to operate; ^g depending on flight altitude; ^h weight of SHU, ICU and display

Suppl. Table S4. List of decommissioned or inactive satellite missions carrying hyperspectral sensors and their specifications (ESA 2018; HSFL ; NRSC-ISRO ; Symbios 2018; USGS)

Satellite	Country	Operational Lifetime ^a	Design Life	Hyperspectral Sensor	Spatial Resolution (m)	Swath Width (km)	Spectral Range (nm)	Spectral Resolution (nm)	Spectral Bands	Revisit (days)	Data Access
EO-1 (Earth Observing-1)	USA	2000-2017	1.5 years (exceeded)	Hyperion	30	7.5	400-1000 (VNIR), 900-2500 (SWIR)	10	220	16	Historical data available in Earth Explorer and GloVis
OrbView-4 minisatellite	USA	2001	5	OHIS (OrbView Hyperspectral Imaging System)	8	5 x 20	450-905 (VNIR), 830-1740 (NIR), 1580-2490 (SWIR)	11.4	40 (VNIR), 80 (NIR), 80 (SWIR)	3	No data due to launch failure
IMS-1 or TWSat (Indian Microsatellite- 1 or Third World Satellite)	India	2008-2013	2 years (exceeded)	HySI (Hyper-Spectral Imager)	505.6	130	400-950	< 15	64	24	Historical data within the Indian region available in NRSC under the Indian Geo- Platform of ISRO
TacSat-3 (Tactical Satellite-3 minisatellite)	USA	2009-2012	6 months (exceeded)	ARTEMIS (Advanced Responsive Tactically Effective Military Imaging Spectrometer)	-		400-2500	5 ^b	400+	-	Inaccessible due to military nature of the mission
HS-1 (HiakaSat ^c microsatellite)	USA	2015	6 months	SUCHI (Space Ultra- compact Hyperspectral Imager)	230	59 x 230	8500-13000	-	7	-	No data due to launch failure

Note: ^a starting from the year of launch; ^b spectral sampling; ^c originally called the HawaiiSat-1 mission but officially carried by the Operationally Responsive Space-4 (ORS-4) mission

Suppl. Table S5. List of launched, operational and planned satellite missions carrying hyperspectral sensors and their specifications (ESA 2018; NRSCC 2017; Satellite Imaging Corp. 2007; Satellogic). This table provides an overview without claiming to be exhaustive.

Satellite	Country	Hyperspectral Sensor	Spatial Resolution (m)	Swath Width (km)	Spectral Range (nm)	Spectral Resolution	Spectral Bands	Revisit (days)	Data Provider/Access
Project for On-Board Autonomy-1 (PROBA-1)	Belgium	CHRIS (Compact High Resolution Imaging Spectrometer)	17	13	400-1050	1.25 nm	19	7	Data available in ESA Earth Online
Aqua	USA	AIRS (Atmospheric Infrared Sounder)	13500 (IR), 2300 (VNIR)	1650 (IR), 40 (VNIR)	3740-15400 (IR), 410-490 (VNIR)	1200 $\lambda/\Delta\lambda$ (IR), 30-450 (VNIR)	2378	16	Data available in Goddard Earth Sciences Data and Information Services Center or GES DISC
Resurs-Prospective 1-5 (Resurs-P 1-5)	Russia	GSA hyperspectral imager	25-30	30	400-1100	5-10 nm	96+	3	Data available for order and tasking at Space Commercial Services Global Information or SCS Gi
Kent Ridge 1 microsatellite (KR1)	Singapore w/ Germany	PPL1 and PPL2 (Primary Payload 1 and 2)	44 m (PPL1), 110 m (PPL2)	47.5 (PPL1), 56.3 (PPL2)	500-900 (PPL1), 900-1500 (PPL2)	-	20-30	-	No available information
Ñusat 1 (Fresco) and Ñusat 1 (Batata)	Argentina	-	30	150	400-900	5 nm	600	-	Data commercially available from Satellogic
Chinese Carbon Dioxide Observation Satellite Mission (TanSat minisatellite)	China	CarbonSpec (Carbon Dioxide Spectrometer)	2000	20	758-778, 1594-1624, 2042-2082	0.044 nm, 0.12 nm, 0.16 nm	-	16	Data available in National Remote Sensing Centre of China (NRSCC)
Gaofen 5 (GF-5)	China	AHSI (Advanced Hyperspectral Imager)	No information available for AHSI						
GomSpace Express 4 cubesats (GOMX-4A and B)	Denmark w/ ESA	HyperScout	40	164	400-1000	-	45	5	No available information yet

Suppl. Table S5 cntd. List of launched, operational and planned satellite missions carrying hyperspectral sensors and their specifications (ASI 2018; Cotten et al. 2016; ESA 2018; Lee et al. 2015; Müller et al. 2012; NASA/JPL ; Symbios 2018; WMO 2011-2018).

Satellite	Country	Hyperspectral Sensor	Spatial Resolution (m)	Swath Width (km)	Spectral Range (nm)	Spectral Resolution (nm)	Spectral Bands	Revisit (days)	Data Provider/Access
Multi-User System for Earth Imaging platform (ISS MUSES)	Germany and USA	DESI (DLR Earth Sensing Imaging Spectrometer)	30	~30	400-1000	2.55 ^b	235	Not indicated ^b	Data to be distributed by Teledyne Technologies Inc. for commercial purposes and by German Aerospace Center (DLR) for scientific purposes
PRecursore IperSpettrale della Missione Applicativa (PRISMA)	Italy	PRISMA	30	30	400-1010 (VNIR), 920-2505 (SWIR)	≤ 12	66 (VNIR), 171 (SWIR)	29 & 7 ^c	Data access description and product request are hosted by the PRISMA website (prisma-i.it)
Spectral Ocean Color cubesat (SPOC)	USA	Hyperspectral Imager	120	75 x 300	400-900	2	100	-	No available information yet.
Advanced Land Observing Satellite-3 (ALOS-3)	Japan	HSS in HISUI (Hyperspectral Sensor in Hyperspectral Imager Suite)	30	30	400-970 (VNIR), 900-2500 (SWIR)	10 (VNIR) ^a , 12.5 (SWIR) ^a	57 (VNIR), 128 (SWIR)	60	Data to be distributed through a network of several ALOS Data Nodes (ADN)
GEO Imaging Satellite (GISAT)	India	HyS-VNIR and HyS-SWIR (Hyperspectral VNIR imager and SWIR imager)	320 (VNIR), 192 (SWIR)	-	400-870 (VNIR), 900-2500 (SWIR)	< 10	60 (VNIR), 150 (SWIR)	30 min the for Indian region	Data within the Indian region only
Environmental Monitoring and Analysis Program (EnMAP)	Germany	HIS (Hyperspectral Imager)	30	30	420-1000 (VNIR), 900-1390 (SWIR I), 1480-1760 (SWIR II), 1950-2450 (SWIR III)	6.5 (VNIR) ^a , 10 (SWIR) ^a	96 (VNIR), 136 (SWIR)	21 & 4 ^d	To be linked to EnMAP Data Access Portal (EDAP)
Hyperspectral Infrared Imager (HyspIRI)	USA	VSWIR Imaging Spectrometer	60	185	380-2500	10	~ 200	19	No available information yet.

^a spectral sampling; ^b average time for the DESIS instrument to scan 90% of the populated Earth is 3-5 days; ^c repeat cycle and relook capability with roll manoeuvre, respectively; ^d repeat cycle and target revisit off nadir, respectively

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