

w = satellite channel spectral bandwidth (μm)

Φ(Ω) = normalized wavelength response function of specific satellite channel

Baseline VGI (I-IV) linear (REG/Stepwise) and non-linear (RSREG) yield models for spring crops

Table 12. SAR and optical VGI (I-IV) linear (REG/Stepwise) and non-linear (RSREG) yield models for spring cereals^{(1),(2)}.

Model category	Factor : Crop /Species ¹⁾	Model (I-IV)	R ²	RMSE kg/ha	Model equation
I Optical	Swh	1.1 (I)	0.764	282.3	$y_b(\text{swh}) = 4941.9 - 5455.9 \times \text{rf3}_{\text{ap}} - 1351.4 \times \text{rf4}_{\text{ap}} + 957.1 \times \text{rf3}_{\text{bp}} + 656.2 \times \text{rf4}_{\text{bp}} + 4742.1 \times \text{rf3}_{\text{cp}} - 4983.5 \times \text{rf4}_{\text{cp}}$
	Swh	1.2 (I)	0.794	42.46	$y_b(\text{swh}) = 985.93 + 13337.46 \times \text{rf3}_{\text{ap}} + 8355.88 \times \text{rf4}_{\text{ap}} - 387.19 \times \text{rf4}_{\text{bp}} + 255.58 \times \text{rf3}_{\text{cp}}$
	Swh	1.3 (II, NDVI)	0.737	297.6	$y_b(\text{swh}, \text{NDVI}) = 4659.2 + 175.4 \times n_{\text{ap}} - 25.6 \times n_{\text{bp}} - 3215.5 \times n_{\text{cp}} + 93.7 \times n_{\text{ap}}^2 - 19.1 \times n_{\text{bp}} \times n_{\text{ap}} - 178.5 \times n_{\text{bp}}^2 - 560.4 \times n_{\text{cp}} \times n_{\text{ap}} + 3250.4 \times n_{\text{cp}} \times n_{\text{bp}} - 864.7 \times n_{\text{cp}}^2$
	Swh	1.4 (II, NDVI)	0.732	300.1	$y_b(\text{swh}, \text{NDVI}) = 4692.90 + 109.84 \times n_{\text{ap}} - 210.38 \times n_{\text{bp}} - 969.22 \times n_{\text{cp}}$
	Swh	1.5 ⁽⁵⁾ (III, GEMI)	0.704	316.1	$Y(\text{swh}, \text{GEMI}) = 5074.1 - 766.2 \times g_{\text{ap}} - 143.1 \times g_{\text{bp}} - 3378.2 \times g_{\text{cp}} + 4254.1 \times g_{\text{ap}}^2 + 1079.8 \times g_{\text{bp}} \times g_{\text{ap}} - 1326.2 \times g_{\text{bp}}^2 - 7264.8 \times g_{\text{cp}} \times g_{\text{ap}} + 7717.2 \times g_{\text{cp}} \times g_{\text{bp}} - 2622.1 \times g_{\text{cp}}^2$
	Swh	1.6 ⁽⁵⁾ (III, GEMI)	0.570	536.8	$y_b(\text{swh}, \text{GEMI}) = 5506.31 + 7780.47 \times g_{\text{ap}} - 12478.3 \times g_{\text{bp}} + 761.96 \times g_{\text{cp}}$
	Swh	1.7 ⁽⁵⁾ (IV, PARND)	0.712	311.6	$y_b(\text{swh}, \text{PAR}_{\text{ND}}) = 4397.9 + 2736.9 \times p_{\text{ap}} - 379.4 \times p_{\text{bp}} - 493.8 \times p_{\text{cp}} - 4235.1 \times p_{\text{ap}}^2 + 2701.1 \times p_{\text{bp}} \times p_{\text{ap}} + 605.8 \times p_{\text{bp}}^2 - 2161.6 \times p_{\text{cp}} \times p_{\text{ap}} + 883.1 \times p_{\text{cp}} \times p_{\text{bp}} + 493.9 \times p_{\text{cp}}^2$
	Swh	1.8 ⁽⁵⁾ (IV, PARND)	0.509	406.3	$Y(\text{swh}, \text{PAR}_{\text{ND}}) = 4502.31 + 529.36 \times p_{\text{ap}} + 2377.05 \times p_{\text{bp}} - 779.31 \times p_{\text{cp}}$
	Brl	2.1 (I)	0.615	449.3	$Y(\text{brl}) = 5348.8 - 600.8 \times \text{rf3}_{\text{ap}} - 184.5 \times \text{rf4}_{\text{ap}} - 8562.4 \times \text{rf3}_{\text{bp}} - 2105.6 \times \text{rf4}_{\text{bp}} - 2766.9 \times \text{rf3}_{\text{cp}} - 1556.2 \times \text{rf4}_{\text{cp}}$
	Brl	2.2 (II, NDVI)	0.611	449.6	$Y(\text{brl}, \text{NDVI}) = 3481.5 - 205.5 \times n_{\text{ap}} - 312.1 \times n_{\text{bp}} + 396.5 \times n_{\text{cp}} - 60.5 \times n_{\text{ap}}^2 - 584.5 \times n_{\text{bp}} \times n_{\text{ap}} + 864.6 \times n_{\text{bp}}^2 + 1081.4 \times n_{\text{cp}} \times n_{\text{ap}} - 710.5 \times n_{\text{cp}} \times n_{\text{bp}} - 232.4 \times n_{\text{cp}}^2$
Brl	2.3 ⁽⁵⁾ (III, GEMI)	0.614	448.6	$Y(\text{brl}, \text{GEMI}) = 5184.0 - 2802.9 \times g_{\text{ap}} - 187.4 \times g_{\text{bp}} - 3457.9 \times g_{\text{cp}} - 374.8 \times g_{\text{ap}}^2 + 91.5 \times g_{\text{bp}} \times g_{\text{ap}} + 1161.4 \times g_{\text{bp}}^2 + 4817.1 \times g_{\text{cp}} \times g_{\text{ap}} - 1932.1 \times g_{\text{cp}} \times g_{\text{bp}} + 2255.6 \times g_{\text{cp}}^2$	
Brl	2.4 ⁽⁵⁾ (IV, PARND)	0.587	463.7	$Y(\text{brl}, \text{PAR}_{\text{ND}}) = 4621.7 + 1852.8 \times p_{\text{ap}} - 6418.5 \times p_{\text{bp}} - 5850.4 \times p_{\text{cp}} + 48.9 \times p_{\text{ap}}^2 - 5952.3 \times p_{\text{bp}} \times p_{\text{ap}} + 10853.0 \times p_{\text{bp}}^2 - 2040.4 \times p_{\text{cp}} \times p_{\text{ap}} + 12879.0 \times p_{\text{cp}} \times p_{\text{bp}} + 6002.9 \times p_{\text{cp}}^2$	
	Oats	2.5 (I)	0.760	55.0	$y_b(\text{oats}) = 3457.4 - 3762.5 \times \text{rf3}_{\text{ap}} - 2135.8 \times \text{rf4}_{\text{ap}} + 6643.1 \times \text{rf3}_{\text{bp}} + 1566.5 \times \text{rf4}_{\text{bp}} + 571.4 \times \text{rf3}_{\text{cp}} - 179.1 \times \text{rf4}_{\text{cp}}$

Table 12. Cont.

		Crop /Species ¹⁾	Model	R ²	RMSE	Model equation
II Optical Species*soil Covariance	Swh * sandy clay	2.6 (I)	0.764	282.3	$Y_b(\text{swhheat,clay}) = 6765.5 - 38407.0 \times rf3_{ap} - 14979.0 \times rf4_{ap} - 23698.0 \times rf3_{bp} + 9552.7 \times rf4_{bp} + 7261.4 \times rf3_{cp} - 22022.0 \times rf4_{cp}$	
	Brl * sandy clay	2.7 (I)	0.166	1382	$Y_b(\text{barley,clay}) = 7141.4 - 3842.1 \times rf3_{ap} - 2612.4 \times rf4_{ap} - 3032.1 \times rf3_{bp} - 11708.0 \times rf4_{bp} - 28637.0 \times rf3_{cp} - 1636.2 \times rf4_{cp}$	
III Optical Species* Cultivar Cov.	Swh* cv. Manu	3.1 (I)	0.089	1292	$Y_b(\text{cv. Manu*clay}) = 5696.5 + 2293.8 \times rf3_{bp} + 5387.9 \times rf3_{cp} - 736396.0 \times (rf3_{bp})^2$	
	Swh * cv. Satu	3.2 (I)	0.046	1031	$Y_b(\text{cv. Satu*clay}) = -9798.2 + 736440.0 \times rf2_{bp} - 9925014.0 \times (rf2_{bp})^2$	
	Brl * cv. Inari	3.3 (I)	0.144	1220	$Y_b(\text{cv. Inari*clay}) = 8336.8 - 71506.0 \times rf3_{bp} - 45627.0 \times (rf3_{bp})^2$	
IV Microwave SAR	Sensor	Cereal specie	Model ⁴⁾	R ²	RMSE	Model equation
	ERS SAR ⁽⁴⁾	Brl	4.1(III)	0.448	482.7	$Y_b(\text{brl, ERS2}) = 4345.7 + 109.4 \times NDVI_{ap} - 211.6 \times NDVI_{bp} - 983.3 \times NDVI_{cp} - 0.57 \times VV_{(5GHz,sp)} + 5.61 \times VV_{(5GHz,dp)}$
		Oats	4.2(III)	0.417	584.2	$Y_b(\text{oats, ERS2}) = 3739.5 + 108.9 \times NDVI_{ap} - 212.1 \times NDVI_{bp} - 938.8 \times NDVI_{cp} - 0.47 \times VV_{(5GHz,sp)} + 4.28 \times VV_{(5GHz,dp)}$
	Radarsat SAR ⁴⁾	Swh	5.1(III)	0.731	300.8	$Y_b(\text{swh, Radarsat}) = 4690.7 + 111.8 \times NDVI_{ap} - 213.4 \times NDVI_{bp} - 982.6 \times NDVI_{cp} - 2.69 \times HH_{(5GHz,sp)} + 3.9 \times HH_{(5GHz,dp)}$
		Brl	5.2(III)	0.702	322.8	$Y_b(\text{brl, Radarsat}) = 4430.1 + 109.4 \times NDVI_{ap} - 211.6 \times NDVI_{bp} - 983.3 \times NDVI_{cp} - 0.52 \times HH_{(5GHz,sp)} + 5.07 \times HH_{(5GHz,dp)}$
		Oats	5.3(III)	0.624	483.6	$Y_b(\text{oats, Radarsat}) = 3843.3 + 108.9 \times NDVI_{ap} - 212.1 \times NDVI_{bp} - 983.8 \times NDVI_{cp} - 0.47 \times HH_{(5GHz,sp)} + 4.03 \times HH_{(5GHz,dp)}$
	Envisat ASAR ⁽⁴⁾	Swh	6.1(III)	0.723	302.1	$Y_b(\text{swh, Envisat}) = 4701.1 + 108.2 \times NDVI_{ap} - 208.8 \times NDVI_{bp} - 983.1 \times NDVI_{cp} - 3.9 \times VH_{(5GHz,sp)} + 17.4 \times VV_{(5GHz,sp)} - 3.1 \times VH_{(5GHz,dp)} + 5.2 \times VV_{(5GHz,dp)}$
		Brl	6.2(III)	0.694	349.8	$Y_b(\text{brl, Envisat}) = 4261.4 + 109.4 \times NDVI_{ap} - 211.6 \times NDVI_{bp} - 983.3 \times NDVI_{cp} - 4.59 \times VH_{(5GHz,sp)} + 18.24 \times VV_{(5GHz,sp)} - 4.04 \times VH_{(5GHz,dp)} + 6.15 \times VV_{(5GHz,dp)}$
		Oats	6.3(III)	0.617	389.7	$Y_b(\text{oats, Envisat}) = 3635.7 + 108.9 \times NDVI_{ap} - 212.8 \times NDVI_{bp} - 983.8 \times NDVI_{cp} - 2.59 \times VH_{(5GHz,sp)} + 16.46 \times VV_{(5GHz,sp)} - 2.03 \times VH_{(5GHz,dp)} + 4.05 \times VV_{(5GHz,dp)}$
	HUTSCAT Scatterometer ^{(3),(4)}	Swh	7.1(III)	0.582	416.8	$Y_b(\text{swh, HUTSCAT}) = 4258.4 + 109.4 \times NDVI_{ap} - 198.2 \times NDVI_{bp} - 937.4 \times NDVI_{cp} + 5.2 \times VV_{(5GHz,sp)} + 18.4 \times HH_{(5GHz,sp)} - 2.9 \times VH_{(5GHz,sp)} - 16.4 \times HV_{(5GHz,sp)} + 4.4 \times VV_{(5GHz,dp)} + 12.4 \times HH_{(5GHz,dp)} - 2.3 \times VH_{(5GHz,dp)} - 14.4 \times HV_{(5GHz,dp)}$
		Brl	7.2(III)	0.518	490.1	$Y_b(\text{brl, HUTSCAT}) = 4294.2 + 107.2 \times NDVI_{ap} - 209.2 \times NDVI_{bp} - 928.2 \times NDVI_{cp} + 3.2 \times VV_{(5GHz,sp)} + 17.4 \times HH_{(5GHz,sp)} - 3.9 \times VH_{(5GHz,sp)} - 15.4 \times HV_{(5GHz,sp)} + 5.4 \times VV_{(5GHz,dp)} + 11.4 \times HH_{(5GHz,dp)} - 4.3 \times VH_{(5GHz,dp)} - 15.4 \times HV_{(5GHz,dp)}$
		Oats	7.3(III)	0.424	544.2	$Y_b(\text{oats, HUTSCAT}) = 3782.5 + 106.8 \times NDVI_{ap} - 207.2 \times NDVI_{bp} - 942.5 \times NDVI_{cp} + 4.2 \times VV_{(5GHz,sp)} + 15.2 \times HH_{(5GHz,sp)} - 5.9 \times VH_{(5GHz,sp)} - 17.1 \times HV_{(5GHz,sp)} + 4.8 \times VV_{(5GHz,dp)} + 11.8 \times HH_{(5GHz,dp)} - 4.3 \times VH_{(5GHz,dp)} - 12.2 \times HV_{(5GHz,dp)}$

⁽¹⁾ For abbreviations refer to Table 9 ⁽²⁾ Independent variables classified with SatPhenClass-algorithm (Figure 3a,b). ⁽³⁾ HUTSCAT used for calibration verification purposes only (helicopter mounted) ⁽⁴⁾ Only in Part I (SAR+Optical models) ⁽⁵⁾ Only in Part II (Optical models)

Appendix D. SatPhenClass Classification Algorithm for Satellite Data

Appendix figures and tables can be downloaded from the link:

<http://koti.arnas.fi/~hlaurila/download/Pb4>.

The SatPhenClass classification algorithm can be downloaded from the link:

<http://koti.arnas.fi/~hlaurila/download/Pb4> file: SatPhenClass-Appendix.pdf

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