

**Current status and future opportunities for grain protein prediction using on-
and off-combine sensors: a synthesis-analysis**

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11 Supplementary Material

Supplementary Table S1. Summary of the selected studies for the review analysis including entry identification, citation, crop, and sensor-specific characteristics including sensor type, spatial resolution, the best type of spectral feature and columns identifying whether the best type of spectral feature included or not the bands of blue (400-500 nm), green (500-600 nm), red (600-700 nm), red-edge (RE, 700-800 nm), near-infrared (NIR, 800-1300 nm), and short-wave infrared (1300-1900 nm), and grain protein concentration model fit metrics. Max=maximum, Min=minimum, RMSE=root mean square error.

Entry ID.	Citation	Crop	Sensor type	Spatial resolution (m)	Best type of spectral feature	Blue	Green	Red	RE	NIR	SWIR	Max R2	Min RMSE (%)
3a	[35]	Barley	Remote	30	swir	No	No	No	No	No	Yes	0.71	0.17
3b	[35]	Sorghum	Remote	30	nir	No	No	No	No	Yes	No	0.03	
3c	[35]	Wheat	Remote	15	nir	No	No	No	No	Yes	No	0.22	
3d	[35]	Wheat	Remote	30	nir	No	No	No	No	Yes	No	0.64	
4a	[41]	Wheat	Remote	2.5	SR(nir,r)	No	No	Yes	No	Yes	No	0.35	
4b	[41]	Wheat	Remote	1	nir	No	No	No	No	Yes	No	0.36	
8	[44]	Wheat	Proximal		ND(g,b)	Yes	Yes	No	No	No	No	0.97	
10a	[46]	Wheat	Remote	2.5	nir-r	No	No	Yes	No	Yes	No	0.5	
10b	[46]	Wheat	Remote	1	ND(nir,g)	No	Yes	No	No	Yes	No	0.53	
10c	[46]	Wheat	Proximal		nir	No	No	No	No	Yes	No	0.63	
10d	[46]	Wheat	Proximal		ND(nir,r)	No	No	Yes	No	Yes	No	0.63	
11	[34]	Wheat	Proximal		ND(g,r)	No	Yes	Yes	No	No	No	0.45	
14a	[49]	Wheat	Proximal		ND(g,r)	No	Yes	Yes	No	No	No	0.45	
14b	[49]	Wheat	Remote	30	swir	No	No	No	No	No	Yes	0.5	
15	[50]	Wheat	Proximal		First derivative of raw spectra	Yes	Yes	Yes	Yes	Yes	Yes	0.92	0.5

16	[51]	Wheat	Remote	30	HH+SIPI (nir-b/nir-red)	Yes	No	Yes	No	Yes	No	0.56	
18	[53]	Barley	Proximal		REIP	No	No	No	Yes	No	No	0.77	
19a	[54]	Wheat	Remote	0.4	ND(nir,r)	No	No	Yes	No	Yes	No	0.57	0.94
19b	[54]	Wheat	Proximal		ND(nir,r)	No	No	Yes	No	Yes	No	0.7	0.78
21	[56]	Barley	Proximal		TCARI	No	Yes	Yes	Yes	No	No	0.78	
22	[57]	Wheat	Proximal		SR(nir,g)	No	Yes	No	No	Yes	No	0.79	0.65
23a	[58]	Wheat	Remote	15	ND(g,r)	No	Yes	Yes	No	No	No	0.74	1.65
23b	[58]	Wheat	Proximal		ND(g,r)	No	Yes	Yes	No	No	No	0.77	0.89
25	[60]	Wheat	Remote	0.5	Red-edge-Mean-Slope	No	No	No	Yes	No	No	0.65	
29	[62]	Wheat	Proximal		ND(nir,r)	No	No	Yes	No	Yes	No	0.62	
31b	[64]	Barley	Remote	23.5	SR(swir,g swir,r nir,g nir,r)	No	Yes	Yes	No	Yes	Yes	0.61	0.66
31c	[64]	Barley	Remote	10	SR(swir,g swir,r nir,g nir,r)	No	Yes	Yes	No	Yes	Yes	0.51	0.57
32	[65]	Wheat	Remote	2.5	ND(nir,g)	No	Yes	No	No	Yes	No	0.28	
33	[66]	Wheat	Remote	1000	ND(nir,r)	No	No	Yes	No	Yes	No	0.64	
34	[67]	Rice	Remote		ND(b,swir uv,b) + band(nir swir)	Yes	No	No	No	Yes	Yes	0.8	
36	[69]	Wheat	Remote	1000	ND(nir,r)	No	No	Yes	No	Yes	No	0.62	
37	[29]	Rice	Remote	0.23	ND(nir,g)	No	Yes	No	No	Yes	No	0.51	0.25
43	[71]	Wheat	Proximal		ND(nir,r)	No	No	Yes	No	Yes	No	0.74	
44	[72]	Wheat	Remote	1000	ND(nir,r)	No	No	Yes	No	Yes	No	0.62	
46	[74]	Wheat	Proximal		ND(nir,r)	No	No	Yes	No	Yes	No	0.76	
48	[76]	Wheat	Remote	10	nir/(r+g)	No	Yes	Yes	No	Yes	No	0.8	1.28
49	[77]	Wheat	Proximal		TCARI	No	Yes	Yes	Yes	No	No	0.52	0.64
50	[78]	Wheat	Proximal		ND(nir,re)	No	No	No	Yes	Yes	No	0.52	1.53
51	[79]	Wheat	Proximal		MSR+ND(nir,re)	No	No	Yes	Yes	Yes	No	0.77	1.16
52a	[80]	Wheat	Remote	1000	fPAR	Yes	Yes	Yes	No	No	No	0.57	
52b	[80]	Wheat	Remote	250	ND(nir,r)	No	No	Yes	No	Yes	No	0.45	
53	[81]	Wheat	Remote	0.04	REIP	No	No	No	Yes	No	No	0.86	0.61
54	[25]	Wheat	Proximal		ND(nir,r)	No	No	Yes	No	Yes	No	0.69	1.09
56	[83]	Wheat	Remote	6.5	ND(nir,r)	No	No	Yes	No	Yes	No	0.67	
57	[6]	Wheat	Proximal		NRERI (nir-re/nir-r)	No	No	Yes	Yes	Yes	No	0.73	

59	[84]	Wheat	Proximal		ND(nir,r)	No	No	Yes	No	Yes	No	0.48				
60	[28]	Wheat	Remote	1	ND(re,g)	No	Yes	No	Yes	No	No	0.21	0.45			
62a	[86]	Wheat	Remote	30	ND(nir,g)	No	Yes	No	No	Yes	No	0.48				
62b	[86]	Wheat	Remote	2.5	ND(nir,g)	No	Yes	No	No	Yes	No	0.47				
62c	[86]	Wheat	Remote	6.5	ND(nir,re)	No	No	No	Yes	Yes	No	0.51				
62d	[86]	Wheat	Remote	1.8	ND(nir,re)	No	No	No	Yes	Yes	No	0.55				
62e	[86]	Wheat	Remote	10	ND(nir,re)	No	No	No	Yes	Yes	No	0.56				
62f	[86]	Wheat	Proximal		ND(774,742)	No	No	No	Yes	No	No	0.56				
65	[87]	Wheat	Proximal		IREC+CVI	No	Yes	Yes	Yes	Yes	No	0.47				
68	[26]	Rice	Remote	0.018	ND(nir,g)	No	Yes	No	No	Yes	No	0.8	0.34			
69	[90]	Wheat	Proximal		MCARI/MTVI2	No	Yes	Yes	Yes	Yes	No	0.85	1.02			
73	[31]	Wheat	Remote	10	EVI	No	Yes	Yes	No	Yes	No	0.52	0.38			
77	[97]	Wheat	Proximal		ND(nir,r)	No	No	Yes	No	Yes	No	0.05				
78	[98]	Wheat	Proximal		SR(nir,r)	No	No	Yes	No	Yes	No	0.14				
79	[99]	Wheat	Remote	10	ND(nir,r)	No	No	Yes	No	Yes	No	0.66				
80	[100]	Wheat	Proximal		ND(nir,r)	No	No	Yes	No	Yes	No	0.99				
81	[101]	Wheat	Remote	0.06	ND(nir,re)	No	No	No	Yes	Yes	No	0.6	1.48			
84	[104]	Wheat	Remote		ND(nir,r)	No	No	Yes	No	Yes	No	0.74				
					Spatial	Best type						Min				
					Sensor	resolution	of spectral						Max	RMSE		
Entry ID.	Citation	Crop	type	(m)	feature				Blue	Green	Red	RE	NIR	SWIR	R2	(%)
3a	Basnet et al., 2003	Barley	Remote	30	swir				No	No	No	No	No	Yes	0.71	
3b	Basnet et al., 2003	Sorghum	Remote	30	nir				No	No	No	No	Yes	No	0.03	
3c	Basnet et al., 2003	Wheat	Remote	15	nir				No	No	No	No	Yes	No	0.22	
3d	Basnet et al., 2003	Wheat	Remote	30	nir				No	No	No	No	Yes	No	0.64	
4a	Wright et al., 2003	Wheat	Remote	2.5	SR(nir,r)				No	No	Yes	No	Yes	No	0.35	
4b	Wright et al., 2003	Wheat	Remote	1	nir				No	No	No	No	Yes	No	0.36	

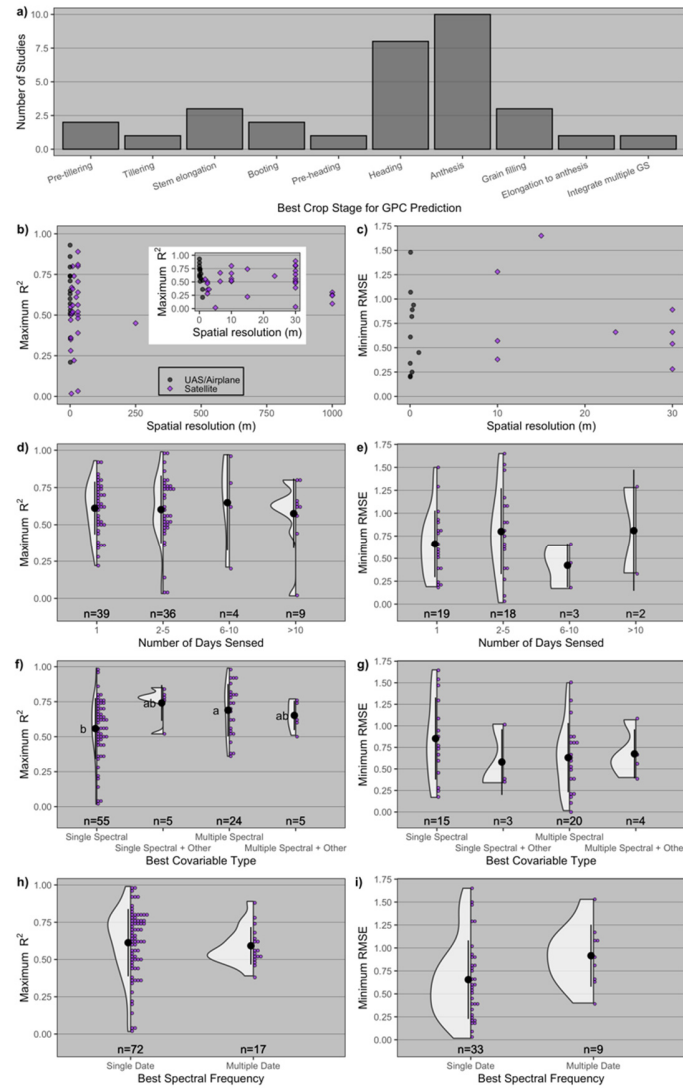
8	Wang et al., 2004	Wheat	Proximal		ND(g,b)	Yes	Yes	No	No	No	No	0.97	0.17
10a	Wright et al., 2004	Wheat	Remote	2.5	nir-r	No	No	Yes	No	Yes	No	0.5	
10b	Wright et al., 2004	Wheat	Remote	1	ND(nir,g)	No	Yes	No	No	Yes	No	0.53	
10c	Wright et al., 2004	Wheat	Proximal		nir	No	No	No	No	Yes	No	0.63	
10d	Wright et al., 2004	Wheat	Proximal		ND(nir,r)	No	No	Yes	No	Yes	No	0.63	
11	Zhao et al., 2004	Wheat	Proximal		ND(g,r)	No	Yes	Yes	No	No	No	0.45	
14a	Zhao et al., 2005	Wheat	Proximal		ND(g,r)	No	Yes	Yes	No	No	No	0.45	
14b	Zhao et al., 2005	Wheat	Remote	30	swir	No	No	No	No	No	Yes	0.5	
15	Apan et al., 2006	Wheat	Proximal		First derivative of raw spectra	Yes	Yes	Yes	Yes	Yes	Yes	0.92	0.5
16	Liu et al., 2006	Wheat	Remote	30	HH+SIPI (nir-b/nir-red)	Yes	No	Yes	No	Yes	No	0.56	
18	Petterson et al., 2006	Barley	Proximal		REIP	No	No	No	Yes	No	No	0.77	
19a	Reyniers et al., 2006	Wheat	Remote	0.4	ND(nir,r)	No	No	Yes	No	Yes	No	0.57	0.94
19b	Reyniers et al., 2006	Wheat	Proximal		ND(nir,r)	No	No	Yes	No	Yes	No	0.7	0.78
21	Pettersson et al., 2007	Barley	Proximal		TCARI	No	Yes	Yes	Yes	No	No	0.78	
22	Xue et al., 2007	Wheat	Proximal		SR(nir,g)	No	Yes	No	No	Yes	No	0.79	0.65
23a	Huang et al., 2008	Wheat	Remote	15	ND(g,r)	No	Yes	Yes	No	No	No	0.74	1.65
23b	Huang et al., 2008	Wheat	Proximal		ND(g,r)	No	Yes	Yes	No	No	No	0.77	0.89
25	Papale et al., 2008	Wheat	Remote	0.5	Red-edge-Mean-Slope	No	No	No	Yes	No	No	0.65	
29	Qualm et al., 2010	Wheat	Proximal		ND(nir,r)	No	No	Yes	No	Yes	No	0.62	
31b	Soderstrom et al., 2010	Barley	Remote	23.5	SR(swir,g swir,r nir,g nir,r)	No	Yes	Yes	No	Yes	Yes	0.61	0.66
31c	Soderstrom et al., 2010	Barley	Remote	10	SR(swir,g swir,r nir,g nir,r)	No	Yes	Yes	No	Yes	Yes	0.51	0.57

32	Song et al., 2010	Wheat	Remote	2.5	ND(nir,g)	No	Yes	No	No	Yes	No	0.28	
33	Guasconi et al., 2011	Wheat	Remote	1000	ND(nir,r)	No	No	Yes	No	Yes	No	0.64	
34	Han-ya et al., 2011	Rice	Remote		ND(b,swir uv,b) + band(nir swir)	Yes	No	No	No	Yes	Yes	0.8	
36	Orlandini et al., 2011	Wheat	Remote	1000	ND(nir,r)	No	No	Yes	No	Yes	No	0.62	
37	Ryu et al., 2011	Rice	Remote	0.23	ND(nir,g)	No	Yes	No	No	Yes	No	0.51	0.25
43	Schoch, 2013	Wheat	Proximal		ND(nir,r)	No	No	Yes	No	Yes	No	0.74	
44	Feng et al., 2014	Wheat	Remote	1000	ND(nir,r)	No	No	Yes	No	Yes	No	0.62	
46	Macnack et al., 2014	Wheat	Proximal		ND(nir,r)	No	No	Yes	No	Yes	No	0.76	
48	Wang et al., 2014	Wheat	Remote	10	nir/(r+g)	No	Yes	Yes	No	Yes	No	0.8	1.28
49	Xu et al., 2014	Wheat	Proximal		TCARI	No	Yes	Yes	Yes	No	No	0.52	0.64
50	Li et al., 2015a	Wheat	Proximal		ND(nir,re)	No	No	No	Yes	Yes	No	0.52	1.53
51	Li et al., 2015b	Wheat	Proximal		MSR+ND(nir,re)	No	No	Yes	Yes	Yes	No	0.77	1.16
52a	Orlando et al., 2015	Wheat	Remote	1000	fPAR	Yes	Yes	Yes	No	No	No	0.57	
52b	Orlando et al., 2015	Wheat	Remote	250	ND(nir,r)	No	No	Yes	No	Yes	No	0.45	
53	Geipel et al., 2016	Wheat	Remote	0.04	REIP	No	No	No	Yes	No	No	0.86	0.61
54	Magney et al., 2016	Wheat	Proximal		ND(nir,r)	No	No	Yes	No	Yes	No	0.69	1.09
56	Mengmeng et al., 2017	Wheat	Remote	6.5	ND(nir,r)	No	No	Yes	No	Yes	No	0.67	
57	Klem et al., 2018	Wheat	Proximal		NRERI (nir-re/nir-r)	No	No	Yes	Yes	Yes	No	0.73	
59	Rellafor, 2018	Wheat	Proximal		ND(nir,r)	No	No	Yes	No	Yes	No	0.48	
60	Rodrigues et al., 2018	Wheat	Remote	1	ND(re,g)	No	Yes	No	Yes	No	No	0.21	0.45
62a	Prey & Schmidhalter, 2019	Wheat	Remote	30	ND(nir,g)	No	Yes	No	No	Yes	No	0.48	

62b	Prey & Schmidhalter, 2019	Wheat	Remote	2.5	ND(nir,g)	No	Yes	No	No	Yes	No	0.47	
62c	Prey & Schmidhalter, 2019	Wheat	Remote	6.5	ND(nir,re)	No	No	No	Yes	Yes	No	0.51	
62d	Prey & Schmidhalter, 2019	Wheat	Remote	1.8	ND(nir,re)	No	No	No	Yes	Yes	No	0.55	
62e	Prey & Schmidhalter, 2019	Wheat	Remote	10	ND(nir,re)	No	No	No	Yes	Yes	No	0.56	
62f	Prey & Schmidhalter, 2019	Wheat	Proximal		ND(774,742)	No	No	No	Yes	No	No	0.56	
65	Zhao et al., 2019	Wheat	Proximal		IREC+CVI	No	Yes	Yes	Yes	Yes	No	0.47	
68	Hama et al., 2020	Rice	Remote	0.018	ND(nir,g)	No	Yes	No	No	Yes	No	0.8	0.34
69	Li et al., 2020	Wheat	Proximal		MCARI/MTVI2	No	Yes	Yes	Yes	Yes	No	0.85	1.02
73	Xu et al., 2020	Wheat	Remote	10	EVI	No	Yes	Yes	No	Yes	No	0.52	0.38
77	Kizilgeci et al., 2021	Wheat	Proximal		ND(nir,r)	No	No	Yes	No	Yes	No	0.05	
78	Sandhu et al., 2021	Wheat	Proximal		SR(nir,r)	No	No	Yes	No	Yes	No	0.14	
79	Santaga et al., 2021	Wheat	Remote	10	ND(nir,r)	No	No	Yes	No	Yes	No	0.66	
80	Savasli et al., 2021	Wheat	Proximal		ND(nir,r)	No	No	Yes	No	Yes	No	0.99	
81	Veverka et al., 2021	Wheat	Remote	0.06	ND(nir,re)	No	No	No	Yes	Yes	No	0.6	1.48
84	Fu et al., 2022	Wheat	Remote		ND(nir,r)	No	No	Yes	No	Yes	No	0.74	

17 *SR(band1, band2) is the simple ratio of band1 divided by band2; ND(band1, band2) is the normalized difference between bands
18 (band1 – band2/band1 + band2) where band is either a category (b=blue, g=green, r=red, re=red-edge, nir=near infrared, swir=short-
19 wave infrared, uv=ultra-violet) or a number (wavelength, in nm); FDRS=first derivative of raw spectra, HH=horizontal-horizontal
20 radar backscatter, SIPI=structure insensitive pigment index, REIP=red-edge inflection point, REMS=red-edge mean slope,
21 TCARI=transformed chlorophyll in absorption index, MSR=modified simple ratio, fPAR=fraction of absorbed photosynthetically

- 22 active radiation, IREC=inverted red-edge chlorophyll index, CVI=chlorophyll vegetation index, MCARI/MTVI2=ratio between the
- 23 modified chlorophyll absorption in reflectance index and the modified triangular vegetation index 2, EVI=enhanced vegetation index.



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25 **Supplementary Figure S1. Best crop stage for grain protein concentration (GPC) prediction**

26 based on maximum R^2 (a), and distribution of maximum R^2 and minimum root mean squared

27 error (RMSE) explained by spatial resolution of remote sensors (b-c), number of days sensed by

28 proximal and remote sensors (d-e), best covariable type (f-g), and best spectral frequency (h-i). n

29 is the number of observations for each distribution. Black dot and lines represent the mean \pm

30 standard deviation. In panel f, means followed by the same letter are not significantly different at

31 $\alpha=0.05$.

32