

Supplementary information for Physical model-guided deep learning for enhanced monitoring maize leaf spot at the early stage

Table S5.1 The other fixed inputs of PROSPECT-D

Variable	Unit	Value
Leaf structural parameter	-	1.5
Dry matter content	g/cm ²	0.012
Brown pigment content	-	0
Carotenoids content	µg/cm ²	10
Anthocyanin content	µg/cm ²	0
Water equivalent thickness	cm	0.015

Table S5.2 The other fixed inputs of LESS

Category	Variable	Unit	Value
Sensor	Width	pixels	120
	Height	pixels	400
	Samples	pixels	128
			379.25:2.1, 383.3:2.1, 387.36:2.1, 391.42:2.1,
			395.48:2.1, 399.54:2.1, 403.61:2.1, 407.68:2.1,
			411.75:2.1, 415.83:2.1, 419.91:2.1, 423.99:2.1,
			428.08:2.1, 432.17:2.1, 436.26:2.1, 440.36:2.1,
			444.45:2.1, 448.55:2.1, 452.66:2.1, 456.77:2.1,
			460.88:2.1, 464.99:2.1, 469.11:2.1, 473.23:2.1,
			477.35:2.1, 481.47:2.1, 485.6:2.1, 489.74:2.1,
			493.87:2.1, 498.01:2.1, 502.15:2.1, 506.29:2.1,
			510.44:2.1, 514.59:2.1, 518.74:2.1, 522.9:2.1,
			527.06:2.1, 531.22:2.1, 535.39:2.1, 539.56:2.1,
			543.73:2.1, 547.9:2.1, 552.08:2.1, 556.26:2.1,
			560.44:2.1, 564.63:2.1, 568.82:2.1, 573.01:2.1,
			577.21:2.1, 581.41:2.1, 585.61:2.1, 589.82:2.1,
			594.03:2.1, 598.24:2.1, 602.45:2.1, 606.67:2.1,
	Spectral Bands	nm	610.89:2.1, 615.11:2.1, 619.34:2.1, 623.57:2.1,
			627.8:2.1, 632.04:2.1, 636.28:2.1, 640.52:2.1,
			644.76:2.1, 649.01:2.1, 653.26:2.1, 657.52:2.1,
			661.77:2.1, 666.03:2.1, 670.3:2.1, 674.56:2.1,
			678.83:2.1, 683.11:2.1, 687.38:2.1, 691.66:2.1,
			695.94:2.1, 700.23:2.1, 704.51:2.1, 708.81:2.1,
			713.1:2.1, 717.4:2.1, 721.7:2.1, 726.0:2.1, 730.31:2.1,
			734.62:2.1, 738.93:2.1, 743.24:2.1, 747.56:2.1,
			751.88:2.1, 756.21:2.1, 760.54:2.1, 764.87:2.1,
			769.2:2.1, 773.54:2.1, 777.88:2.1, 782.22:2.1,

		874.13:2.1, 891.79:2.1, 909.49:2.1, 927.25:2.1, 945.06:2.1, 962.91:2.1, 980.82:2.1, 998.77:2.1, 1003.26:2.1, 1007.76:2.1, 1012.27:2.1, 1016.77:2.1	878.54:2.1, 896.21:2.1, 913.93:2.1, 931.7:2.1, 949.52:2.1, 967.38:2.1, 985.3:2.1, 989.79:2.1, 1003.26:2.1, 1007.76:2.1, 1012.27:2.1, 1016.77:2.1	882.95:2.1, 900.63:2.1, 918.37:2.1, 936.15:2.1, 953.98:2.1, 971.86:2.1, 989.79:2.1, 994.28:2.1, 1003.26:2.1, 1007.76:2.1, 1012.27:2.1, 1016.77:2.1	887.37:2.1, 905.06:2.1, 922.81:2.1, 940.6:2.1, 958.44:2.1, 976.34:2.1, 994.28:2.1, 1012.27:2.1, 1016.77:2.1, 1016.77:2.1	
	Width Extent	m	0.6			
	Height Extent	m	2			
Observation	View Zenith	°	0			
	View Azimuth	°	180			
	Sensor Height	m	50			
Illumination & Atmosphere	Sun Zenith	°	30			
	Sun Azimuth	°	160			
Optical Database	-	-	SIM #1: From PROSPECT-D (Tabel S1)			
	-	-	SIM #2: From database (measured spectra)			
	-	-	SIM #3: From database (mixed spectra)			
Terrain	type	-	PLANE			
	XSize	m	0.6			
	YSize	m	2			
	BRDF Type	-	Lambertian			
	Optical Property	-	Dark soil mollisol			

Table S5.3 Linear regression analysis of simulated reflectance vs. UAV hyperspectral data under varying leaf spot infection levels

DI	Simulations	R ²	RMSE	rRMSE	Slope	Intercept
DI=0%	SIM #1	0.98	0.03	0.10	1.21	0.00
	SIM #2	0.99	0.01	0.06	1.36	0.00
	SIM #3	0.97	0.04	0.15	1.33	0.00
DI=30%	SIM #1	0.98	0.03	0.11	1.13	0.00
	SIM #2	0.99	0.01	0.06	1.34	-0.02
	SIM #3	0.98	0.03	0.11	1.36	-0.03
DI=50%	SIM #1	0.97	0.03	0.13	1.05	0.00
	SIM #2	0.99	0.01	0.05	1.24	-0.01
	SIM #3	0.98	0.03	0.12	1.32	-0.05
DI=70%	SIM #1	0.94	0.04	0.17	0.98	-0.01
	SIM #2	0.99	0.01	0.03	1.11	-0.03
	SIM #3	0.97	0.03	0.13	1.26	-0.06

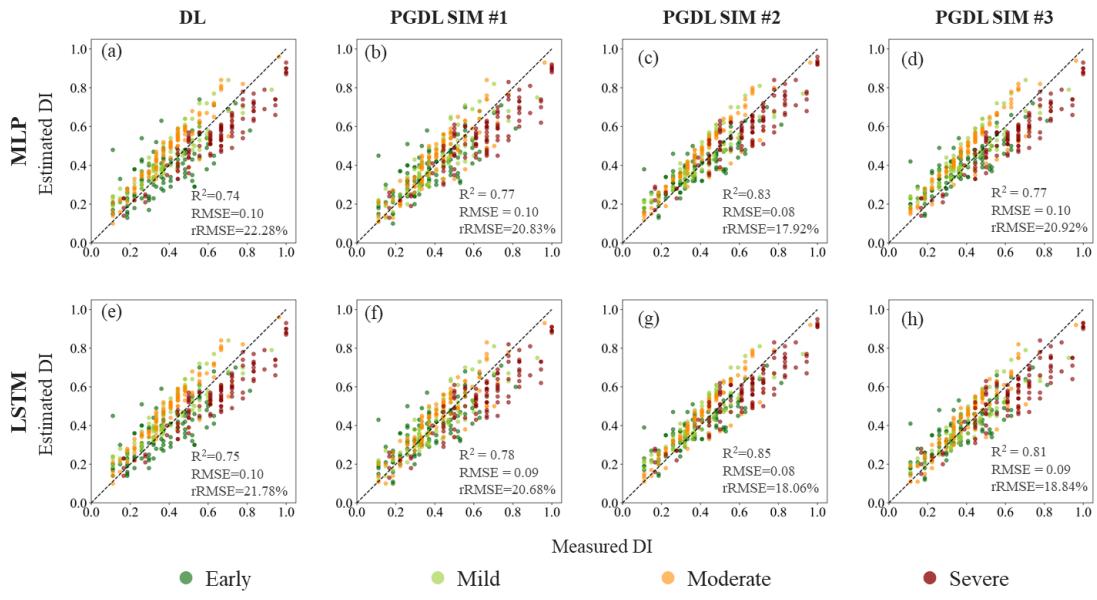


Fig. S5.1. Performance of the MLP- and LSTM-related models for monitoring maize leaf spot disease index (DI) on the 2021 test dataset. All regressions were statistically significant ($p < 0.01$).

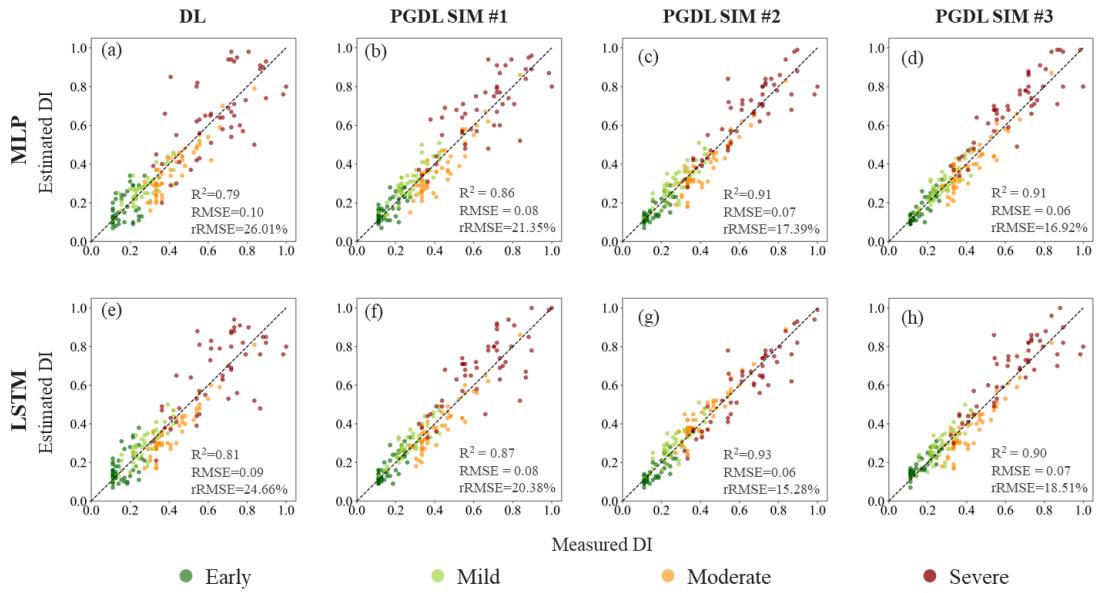


Fig. S5.2. Performance of the MLP- and LSTM-related models for monitoring maize leaf spot disease index (DI) on the 2023 test dataset. All regressions were statistically significant ($p < 0.01$).

Table S5.4 performance of Physically-based Models for monitoring maize leaf spot disease index (DI) across different disease stages in the 2021 and 2023 test sets

Models	Datasets	2021						2023					
		R ²	RMSE	MAE	rRMSE	Intercept	Slope	R ²	RMSE	MAE	rRMSE	Intercept	Slope
Based on SIM #2	Early	0.46	0.11	0.09	30.41%	0.17	0.62	0.30	0.04	0.03	27.60%	0.04	0.76
	Mild	0.54	0.10	0.09	26.16%	0.11	0.85	0.47	0.06	0.05	20.60%	0.04	0.96
	Moderate	0.60	0.10	0.09	24.49%	0.10	0.92	0.32	0.10	0.08	22.90%	-0.10	1.06
	Severe	0.59	0.13	0.11	19.92%	0.05	0.76	0.29	0.15	0.12	22.80%	0.22	0.71
Based on SIM #3	Early	0.47	0.11	0.09	30.17%	0.13	0.62	0.15	0.05	0.04	30.41%	0.04	0.73
	Mild	0.54	0.10	0.09	26.16%	0.11	0.85	0.42	0.06	0.05	21.50%	0.03	0.99
	Moderate	0.58	0.11	0.09	25.19%	0.10	0.92	0.37	0.09	0.08	22.04%	-0.10	1.10
	Severe	0.59	0.13	0.11	20.08%	0.05	0.76	0.18	0.16	0.13	24.57%	0.22	0.70

Table S5.5 performance of MLP-related models for monitoring maize leaf spot disease index (DI) across different disease stages in the 2021 and 2023 test sets

Models	Datasets	2021						2023					
		R ²	RMSE	MAE	rRMSE	Intercept	Slope	R ²	RMSE	MAE	rRMSE	Intercept	Slope
MLP model	Early	0.47	0.11	0.09	30.21%	0.15	0.62	-0.69	0.07	0.05	42.84%	0.05	0.69
	Mild	0.71	0.08	0.07	20.99%	0.12	0.83	0.61	0.05	0.04	17.71%	0.07	0.78
	Moderate	0.67	0.09	0.08	22.18%	0.09	0.93	0.61	0.07	0.06	17.37%	-0.06	1.02
	Severe	0.67	0.12	0.10	18.01%	0.06	0.77	0.15	0.16	0.13	25.00%	0.18	0.73
PGDL-MLP SIM #1	Early	0.58	0.10	0.08	26.97%	0.14	0.63	0.35	0.04	0.03	26.46%	0.03	0.81
	Mild	0.76	0.08	0.06	19.03%	0.08	0.84	0.49	0.06	0.04	20.23%	0.03	1.00
	Moderate	0.78	0.08	0.06	17.99%	0.06	0.90	0.60	0.08	0.06	17.64%	-0.08	1.08
	Severe	0.63	0.12	0.10	18.98%	0.07	0.76	0.50	0.12	0.10	19.20%	0.19	0.76
PGDL-MLP SIM #2	Early	0.73	0.08	0.06	21.70%	0.13	0.65	0.63	0.03	0.02	20.07%	0.02	0.83
	Mild	0.78	0.07	0.06	18.01%	0.10	0.83	0.54	0.05	0.04	19.08%	0.04	0.97

	Moderate	0.76	0.08	0.07	19.03%	0.08	0.92	0.70	0.06	0.05	15.20%	-0.06	1.04
	Severe	0.78	0.09	0.08	14.70%	0.10	0.76	0.70	0.10	0.07	14.84%	0.12	0.85
PGDL-MLP SIM #3	Early	0.68	0.09	0.07	23.41%	0.15	0.64	0.65	0.03	0.02	19.54%	-0.01	1.05
	Mild	0.71	0.08	0.07	20.99%	0.12	0.83	0.70	0.04	0.03	15.47%	0.02	0.99
	Moderate	0.67	0.09	0.09	22.34%	0.10	0.92	0.76	0.06	0.05	13.69%	-0.03	1.02
	Severe	0.67	0.12	0.10	18.01%	0.06	0.77	0.67	0.10	0.09	15.55%	0.13	0.88

Table S5.6 performance of LSTM-related models for monitoring maize leaf spot disease index (DI) across different disease stages in the 2021 and 2023 test sets

Models	Datasets	2021						2023					
		R ²	RMSE	MAE	rRMSE	Intercept	Slope	R ²	RMSE	MAE	rRMSE	Intercept	Slope
LSTM model	Early	0.55	0.10	0.08	27.89%	0.13	0.63	-0.69	0.07	0.05	42.84%	0.06	0.69
	Mild	0.71	0.08	0.07	20.99%	0.12	0.83	0.61	0.05	0.04	17.59%	0.03	0.97
	Moderate	0.67	0.09	0.08	22.18%	0.09	0.93	0.59	0.08	0.06	17.83%	-0.08	1.05
	Severe	0.67	0.12	0.10	18.01%	0.06	0.77	0.29	0.15	0.12	22.92%	0.19	0.73
PGDL-LSTM SIM #1	Early	0.61	0.10	0.07	25.78%	0.13	0.64	0.41	0.04	0.03	25.36%	0.00	1.05
	Mild	0.78	0.07	0.06	18.32%	0.08	0.84	0.63	0.05	0.04	17.24%	0.03	1.00
	Moderate	0.79	0.07	0.06	17.84%	0.06	0.91	0.71	0.06	0.05	14.89%	-0.04	1.02
	Severe	0.61	0.13	0.10	19.55%	0.07	0.76	0.49	0.13	0.10	19.40%	0.20	0.76
PGDL-LSTM SIM #2	Early	0.72	0.08	0.06	21.91%	0.14	0.65	0.56	0.03	0.03	21.83%	0.02	0.80
	Mild	0.78	0.07	0.06	18.01%	0.10	0.83	0.54	0.05	0.04	19.08%	0.04	0.97
	Moderate	0.79	0.07	0.07	17.76%	0.07	0.92	0.82	0.05	0.04	11.68%	0.00	1.04
	Severe	0.75	0.10	0.08	15.57%	0.09	0.76	0.78	0.08	0.06	12.79%	-0.01	0.98
PGDL-LSTM SIM #3	Early	0.68	0.09	0.07	23.54%	0.13	0.64	0.56	0.03	0.03	21.86%	0.03	0.91
	Mild	0.82	0.07	0.06	16.39%	0.08	0.83	0.61	0.05	0.04	17.59%	0.03	0.97
	Moderate	0.80	0.07	0.06	17.31%	0.06	0.92	0.63	0.07	0.06	16.90%	-0.07	1.04
	Severe	0.69	0.11	0.09	17.45%	0.09	0.76	0.65	0.10	0.08	16.03%	0.16	0.81