Appendix for "Management history can cause irreversible changes in agroecosystems: an experimental demonstration"

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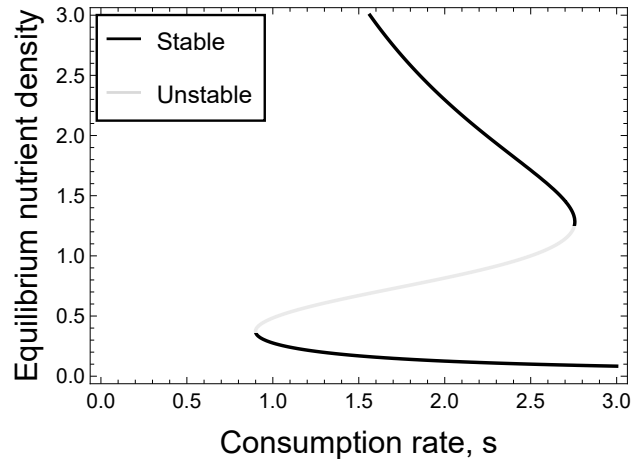## A1: Hysteresis in the *Carpenter* model due to consumption rate

Figure A1: Hysteretic pattern for equation 2 with nutrient input rate $a = 0.25$, recycling rate $r = 4.5$, and source function parameters $m = 1, q = 4$.

A2: Perturbations to infer unstable states

We planned to test for the presence of unstable states by perturbing the system at even inorganic and organic fertilization levels to test for sudden jumps between alternative stable states. It is a standard assumption in hysteresis studies that we observe system only at a stable state, here, that is our measurements at the end of a week after fertilization. Therefore, when we reached 50% inorganic and 50% organic fertilization in our experiment, soils from a subset of our forward and reverse replicates were mixed at a 1:1, 1:2, or 2:1 ratio in order to forcefully move the state of the system to lie in between the two alternative states. We further perturbed the system with $a \pm 1/4$ change to fertilization and observe effects on state variables. We expected that the change in the direction and magnitude of state variables would allow us to infer whether the unstable states in our inferred bifurcation plots curves that are consistent with empirical results and dynamic rules (Fig. 3, 4). However, we had too few replicates and too few perturbation treatments to fully contrast the theoretical prediction with the data. We show the outcomes of the perturbations in Fig. A2, A3.

Figure A2: Perturbations suggest alternative stable states in flux measurements. All the arrows are formed by state variable measurements at the start and end of each week. The vertical arrows represent the perturbations and the outcome. The vertical arrows are the average of three replication for Week 3-4 and the average of two replications for Week 7-8.
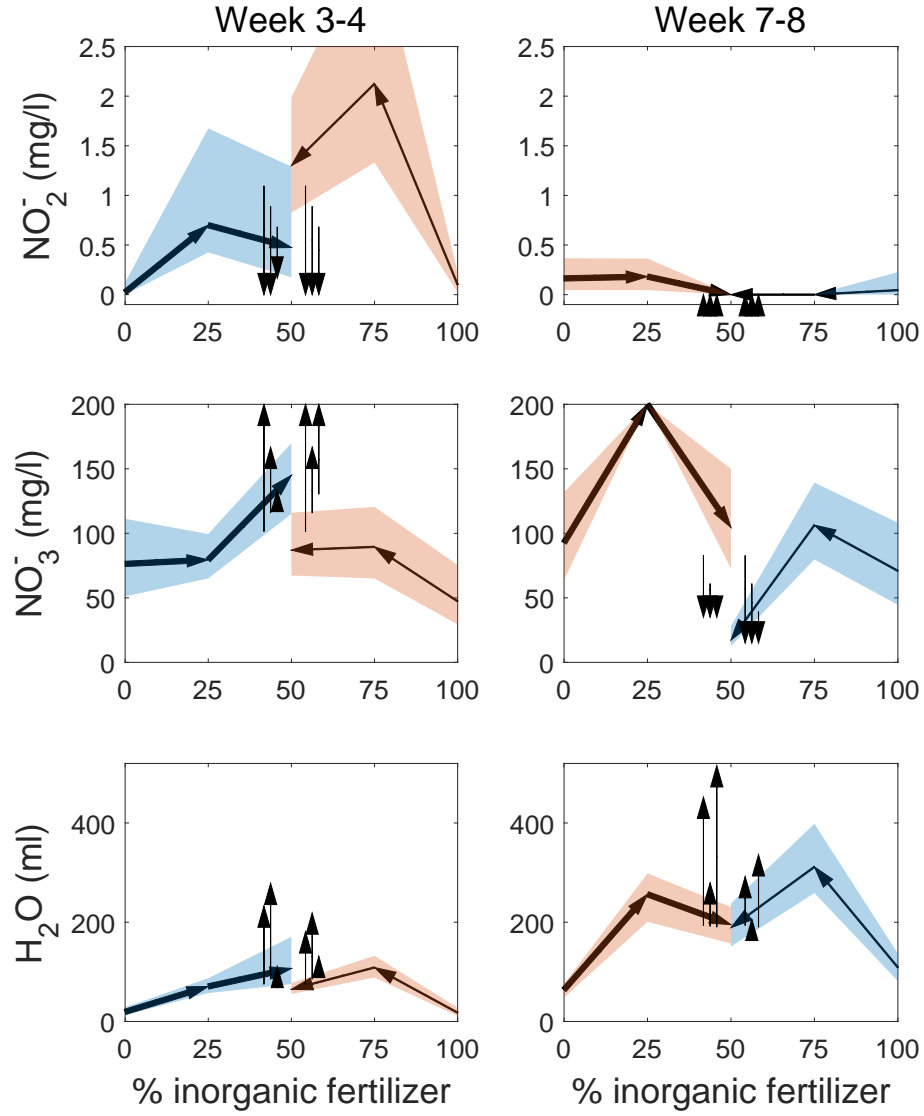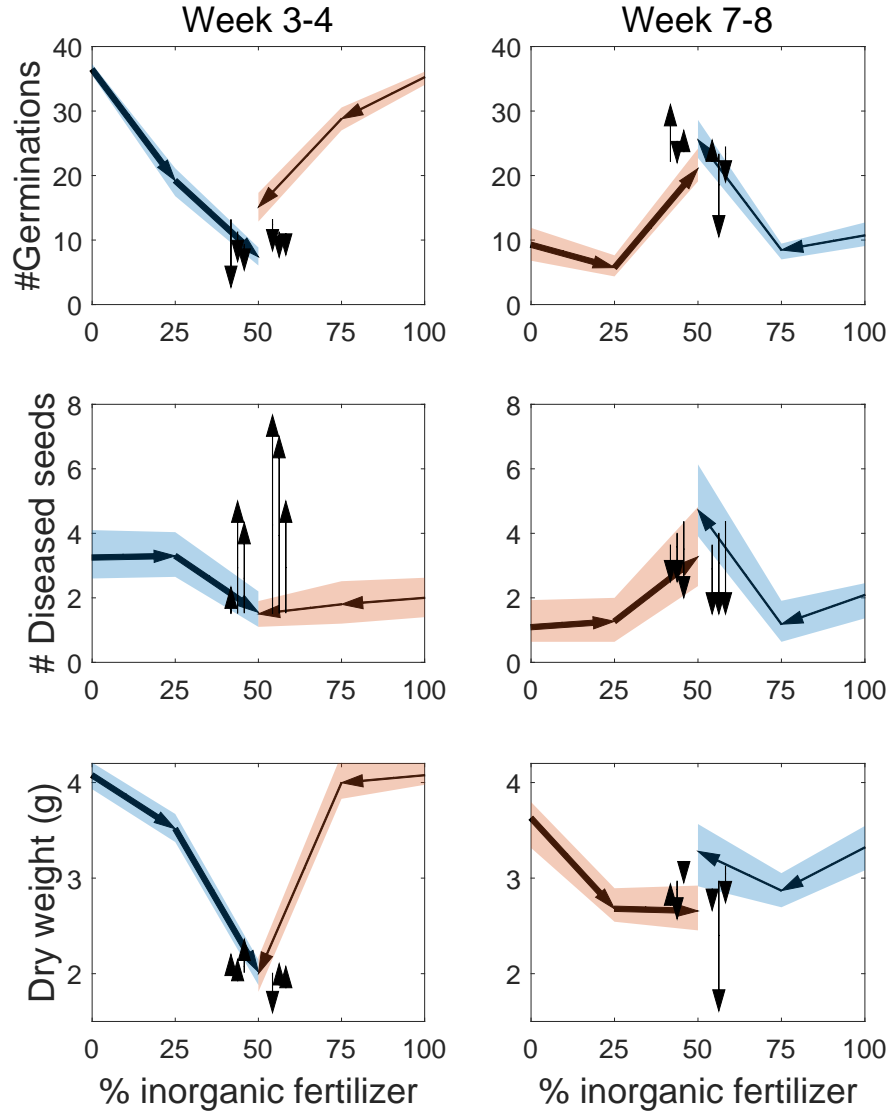
Figure A3: Perturbations suggest alternative stable states in fitness proxies. All the arrows are formed by state variable measurements at the start and end of each week. The vertical arrows represent the perturbations and the outcome. The vertical arrows are the average of three replication for Week 3-4 and the average of two replications for Week 7-8.

A3: ANOVA tables

ANOVA (all)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	15.841	4	3.9603	4.57	0.0014
St. dir.	1.793	1	1.7932	2.07	0.1514
Cur. dir.	6.149	1	6.1486	7.1	0.0082
Fert.:St. dir.	11.42	4	2.855	3.3	0.0118
Fert.:Cur. dir.	14.106	4	3.5265	4.07	0.0033
St. dir.:Cur. dir.	12.607	1	12.6071	14.56	0.0002
Error	202.571	234	0.8657		
Total	291.645	249			

ANOVA (starting forward - ff vs fb)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	1.8524	4	0.4631	1.17	0.329
Dir.	1.4335	1	1.43348	3.61	0.0598
Fert.:Dir.	2.0568	4	0.5142	1.3	0.2758
Error	45.6295	115	0.39678		
Total	55	124			

ANOVA (starting backward - bf vs bb)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	14.088	4	3.5219	2.75	0.0315
Dir.	11.126	1	11.1263	8.69	0.0039
Fert.:Dir.	19.039	4	4.7598	3.72	0.007
Error	147.265	115	1.2806		
Total	226.2	124			

ANOVA (ff vs bb)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	25.398	4	6.34959	5.11	0.0007
Dir.	8.995	1	8.99459	7.25	0.0079
Fert.:Dir.	32.343	4	8.08571	6.51	0.0001
Error	191.185	154	1.24146		
Total	273.004	163			

ANOVA (ff vs bf)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	2.9859	4	0.74646	1.83	0.1276
Dir.	0.8063	1	0.80633	1.98	0.1623
Fert.:Dir.	2.2763	4	0.56908	1.4	0.2398
Error	46.8841	115	0.40769		
Total	55.4829	124			

ANOVA (fb vs bb)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	20.463	4	5.1158	4.03	0.0043
Dir.	13.213	1	13.2127	10.41	0.0016
Fert.:Dir.	21.506	4	5.3764	4.23	0.0031
Error	146.01	115	1.2697		
Total	228.241	124			

ANOVA (fb vs bf)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	0.11898	4	0.02975	1.32	0.2692
Dir.	0.06689	1	0.06689	2.97	0.0886
Fert.:Dir.	0.15754	4	0.03938	1.75	0.1475
Error	1.70909	76	0.02249		
Total	2.175	85			

Figure A4: ANOVA tables for nitrite leaching data. In the two-letter abbreviations, the first letter indicates starting direction and the second letter indicates the direction of transition, where f=forward and b=backward.

ANOVA (all)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	65950.6	4	16487.6	5.41	0.0004
St. dir.	46438.2	1	46438.2	15.23	0.0001
Cur. dir.	4797.9	1	4797.9	1.57	0.2109
Fert.:St. dir.	109190.3	4	27297.6	8.95	0
Fert.:Cur. dir.	200594.2	4	50148.5	16.45	0
St. dir.:Cur. dir.	39291.3	1	39291.3	12.89	0.0004
Error	713322.2	234	3048.4		
Total	1112200	249			

ANOVA (starting forward - ff vs fb)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	76949.9	4	19237.5	6.58	0.0001
Dir.	66936.9	1	66936.9	22.9	0
Fert.:Dir.	59322.3	4	14830.6	5.07	0.0008
Error	336079.7	115	2922.4		
Total	549868	124			

ANOVA (starting backward - bf vs bb)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	151215.2	4	37803.8	13.39	0
Dir.	133.5	1	133.5	0.05	0.8282
Fert.:Dir.	102493.6	4	25623.4	9.08	0
Error	324616.8	115	2822.8		
Total	562295.2	124			

ANOVA (ff vs bb)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	82183.5	4	20545.9	6.16	0.0001
Dir.	22932.1	1	22932.1	6.88	0.0096
Fert.:Dir.	41484.6	4	10371.2	3.11	0.0171
Error	513590.8	154	3335		
Total	666562	163			

ANOVA (ff vs bf)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	122918	4	30729.5	10.22	0
Dir.	12438.6	1	12438.6	4.14	0.0442
Fert.:Dir.	202991.9	4	50748	16.88	0
Error	345699.7	115	3006.1		
Total	640589.6	124			

ANOVA (fb vs bb)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	39176.2	4	9794	3.58	0.0087
Dir.	18397.5	1	18397.5	6.72	0.0108
Fert.:Dir.	50228	4	12557	4.58	0.0018
Error	314996.8	115	2739.1		
Total	407482.4	124			

ANOVA (fb vs bf)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	36392.7	4	9098.2	4.7	0.0019
Dir.	16176.2	1	16176.2	8.36	0.005
Fert.:Dir.	184027.5	4	46006.9	23.77	0
Error	147105.7	76	1935.6		
Total	439765.3	85			

Figure A5: ANOVA tables for nitrate leaching data.

ANOVA (all)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	1195	4	298.76	7.6	0
St. dir.	120.2	1	120.25	3.06	0.0815
Cur. dir.	16.1	1	16.08	0.41	0.5229
Fert.:St. dir.	3242.1	4	810.53	20.63	0
Fert.:Cur. dir.	10715.1	4	2678.76	68.19	0
St. dir.:Cur. dir.	111.2	1	111.2	2.83	0.0938
Error	9193	234	39.29		
Total	31709.6	249			

ANOVA (starting forward - ff vs fb)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	2824.84	4	706.21	56.99	0
Dir.	37.32	1	37.32	3.01	0.0853
Fert.:Dir.	5234.13	4	1308.53	105.6	0
Error	1424.95	115	12.39		
Total	14360	124			

ANOVA (starting backward - bf vs bb)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	6674.8	4	1668.7	100.56	1.29658e-36
Dir.	527.6	1	527.65	31.8	1.24192e-07
Fert.:Dir.	3867.7	4	966.93	58.27	8.71635e-27
Error	1908.3	115	16.59		
Total	17247.2	124			

ANOVA (ff vs bb)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	4156.7	4	1039.18	70.65	0
Dir.	135	1	134.95	9.18	0.0029
Fert.:Dir.	13742.4	4	3435.59	233.57	0
Error	2265.2	154	14.71		
Total	23229.5	163			

ANOVA (ff vs bf)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	2990.8	4	747.7	55.92	0
Dir.	183	1	183.02	13.69	0.0003
Fert.:Dir.	8586.3	4	2146.58	160.53	0
Error	1537.8	115	13.37		
Total	15819.2	124			

ANOVA (fb vs bb)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	2020.4	4	505.09	32.35	0
Dir.	241.8	1	241.84	15.49	0.0001
Fert.:Dir.	7988.5	4	1997.12	127.92	0
Error	1795.5	115	15.61		
Total	15433.4	124			

ANOVA (fb vs bf)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	2898.07	4	724.517	51.55	0
Dir.	41.1	1	41.101	2.92	0.0913
Fert.:Dir.	2854.31	4	713.577	50.77	0
Error	1068.11	76	14.054		
Total	6806.85	85			

Figure A6: ANOVA tables for germinations data.

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ANOVA (all)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	74.78	4	18.6952	5.83	0.0002
St. dir.	3.1	1	3.101	0.97	0.3262
Cur. dir.	62.53	1	62.5348	19.52	0
Fert.:St. dir.	168.03	4	42.0063	13.11	0
Fert.:Cur. dir.	38.79	4	9.6965	3.03	0.0185
St. dir.:Cur. dir.	0	1	0.0006	0	0.989
Error	749.78	234	3.2042		
Total	1093.34	249			

ANOVA (starting forward - ff vs fb)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	61.65	4	15.4125	6.43	0.0001
Dir.	5.519	1	5.5188	2.3	0.1318
Fert.:Dir.	288.072	4	72.018	30.06	0
Error	275.482	115	2.3955		
Total	629.2	124			

ANOVA (starting backward - bf vs bb)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	36.131	4	9.0327	3.75	0.0067
Dir.	0.101	1	0.1008	0.04	0.8384
Fert.:Dir.	76.921	4	19.2302	7.97	0
Error	277.327	115	2.4115		
Total	387.968	124			

ANOVA (ff vs bb)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	212.078	4	53.0196	20.41	1.64779e-13
Dir.	69.677	1	69.6767	26.82	6.87545e-07
Fert.:Dir.	199.836	4	49.9591	19.23	7.51768e-13
Error	400.009	154	2.5975		
Total	796.049	163			

ANOVA (ff vs bf)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	82.361	4	20.5902	8.05	9.25134e-06
Dir.	50.439	1	50.4392	19.73	2.06395e-05
Fert.:Dir.	128.525	4	32.1312	12.57	1.6259e-08
Error	294.027	115	2.5568		
Total	630.768	124			

ANOVA (fb vs bb)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	60.048	4	15.0121	6.67	0.0001
Dir.	19.673	1	19.6726	8.74	0.0038
Fert.:Dir.	107.228	4	26.8071	11.91	0
Error	258.782	115	2.2503		
Total	447.2	124			

ANOVA (fb vs bf)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	59.67	4	14.9175	7.42	0
Dir.	16.866	1	16.8658	8.39	0.0049
Fert.:Dir.	45.949	4	11.4873	5.71	0.0004
Error	152.8	76	2.0105		
Total	295.209	85			

Figure A7: ANOVA tables for diseased seeds data.

ANOVA (all)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	86539.7	4	21634.9	4.15	0.0029
St. dir.	19391.4	1	19391.4	3.72	0.0549
Cur. dir.	58113.4	1	58113.4	11.15	0.001
Fert.:St. dir.	528683.3	4	132170.8	25.36	0
Fert.:Cur. dir.	214357.6	4	53589.4	10.28	0
St. dir.:Cur. dir.	995931.4	1	995931.4	191.13	0
Error	1219328.4	234	5210.8		
Total	3120685.4	249			

ANOVA (starting forward - ff vs fb)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	164384.7	4	41096.2	5.33	0.0006
Dir.	688610	1	688610	89.27	0
Fert.:Dir.	334937.3	4	83734.3	10.85	0
Error	887126.6	115	7714.1		
Total	2033929.3	124			

ANOVA (starting backward - bf vs bb)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	167874.1	4	41968.5	18.61	8.13663e-12
Dir.	355612.6	1	355612.6	157.65	2.68807e-23
Fert.:Dir.	266546.6	4	66636.7	29.54	6.73496e-17
Error	259401.1	115	2255.7		
Total	1046230.1	124			

ANOVA (ff vs bb)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	97140.9	4	24285.2	9.95	0
Dir.	11504.5	1	11504.5	4.71	0.0314
Fert.:Dir.	84230.2	4	21057.6	8.63	0
Error	375793.7	154	2440.2		
Total	602433.6	163			

ANOVA (ff vs bf)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	359365.5	4	89841.4	23.99	1.91761e-14
Dir.	259237	1	259237	69.22	2.04324e-13
Fert.:Dir.	159633.4	4	39908.3	10.66	2.21529e-07
Error	430680.5	115	3745		
Total	1178379.3	124			

ANOVA (fb vs bb)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	415926.2	4	103981.6	16.7	0
Dir.	840897.5	1	840897.5	135.09	0
Fert.:Dir.	127524.9	4	31881.2	5.12	0.0008
Error	715847.3	115	6224.8		
Total	1936933	124			

ANOVA (fb vs bf)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	62199.5	4	15549.9	1.53	0.201
Dir.	76775.5	1	76775.5	7.57	0.0074
Fert.:Dir.	530695.5	4	132673.9	13.08	0
Error	770734.1	76	10141.2		
Total	1516692.5	85			

Figure A8: ANOVA tables for water leaching data.

ANOVA (all)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	36.444	4	9.11103	26.38	0
St. dir.	2.036	1	2.03589	5.89	0.0159
Cur. dir.	0.046	1	0.04629	0.13	0.7146
Fert.:St. dir.	39.007	4	9.7517	28.24	0
Fert.:Cur. dir.	24.16	4	6.03999	17.49	0
St. dir.:Cur. dir.	2.173	1	2.17331	6.29	0.0128
Error	80.818	234	0.34537		
Total	214.872	249			

ANOVA (starting forward - ff vs fb)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	13.9644	4	3.4911	25.22	0
Dir.	0.3789	1	0.3789	2.74	0.1007
Fert.:Dir.	40.3824	4	10.0956	72.94	0
Error	15.9172	115	0.1384		
Total	91.1799	124			

ANOVA (starting backward - bf vs bb)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	37.86	4	9.4649	60.6	1.93382e-27
Dir.	7.163	1	7.1635	45.86	5.66463e-10
Fert.:Dir.	45.563	4	11.3907	72.93	1.20811e-30
Error	17.962	115	0.1562		
Total	123.403	124			

ANOVA (ff vs bb)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	75.077	4	18.7693	130.12	0
Dir.	1.842	1	1.8423	12.77	0.0005
Fert.:Dir.	53.605	4	13.4014	92.91	0
Error	22.214	154	0.1442		
Total	161.727	163			

ANOVA (ff vs bf)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	46.615	4	11.6538	90.04	1.6674e-34
Dir.	2.475	1	2.4751	19.12	2.70633e-05
Fert.:Dir.	35.487	4	8.8718	68.54	1.4974e-29
Error	14.885	115	0.1294		
Total	109.78	124			

ANOVA (fb vs bb)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	27.15	4	6.78754	41.09	2.37616e-21
Dir.	2.954	1	2.95411	17.89	4.73158e-05
Fert.:Dir.	35.611	4	8.90275	53.9	1.64138e-25
Error	18.994	115	0.16517		
Total	102.753	124			

ANOVA (fb vs bf)

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Fert.	8.3054	4	2.07634	13.53	0
Dir.	0.6848	1	0.68481	4.46	0.038
Fert.:Dir.	33.6709	4	8.41772	54.84	0
Error	11.6654	76	0.15349		
Total	49.3775	85			

Figure A9: ANOVA tables for dry weight data.
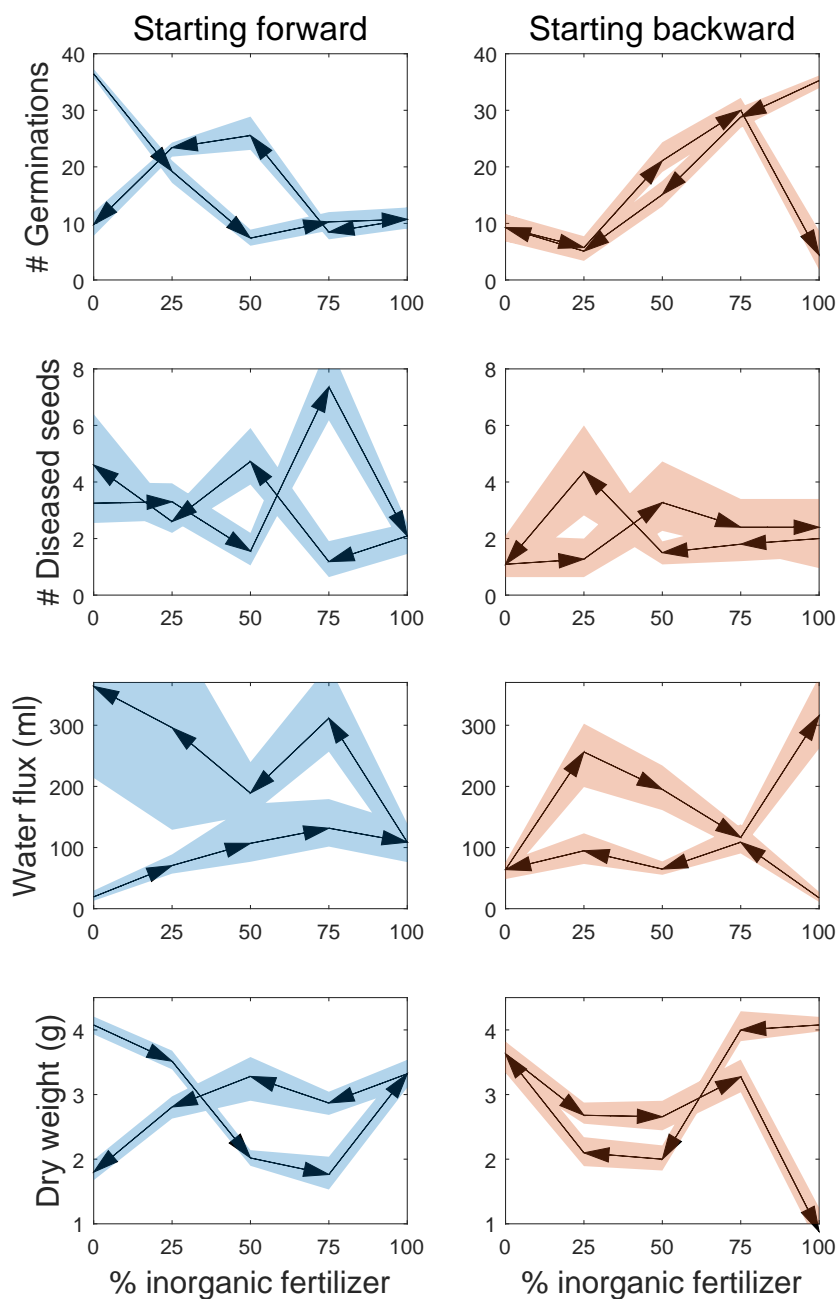
A4: Results for germination, disease incidence, water flux and yield

Figure A10: Complex dynamics in greenhouse experiments.