



N-leaching under lucerne: final report 2015



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September 2015

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LC2398

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Summary

Project and Client

Lake Taupō Protection Trust (LTPT) and the Sustainable Farming Fund (SFF) have funded a four year field trial on N-leaching under cut-and-carry lucerne on a Taupo Lake Care (TLC) member's Tihoi farm. At this site an underground facility is used to collect leachate from large diameter lysimeters. The leaching data will be used by the Overseer® Committee to update the lucerne module within Overseer®.

Objective

- To quantify N-leaching from lysimeters cultivated and planted with lucerne, or lucerne with topsoil amended with 10 t/ha biochar, and established ryegrass/clover.

Methods

- A lysimeter facility at Tihoi was established that contained large barrel lysimeters (1 m diameter × 1.5 m high).

The 12 barrel lysimeters contained 4 replicates each of:

- lysimeters cultivated and planted with lucerne
- lysimeters cultivated, amended with 10 t/ha biochar and planted with lucerne
- lysimeters of established ryegrass/clover
- Lucerne was harvested (cut and carry) at approximately 10% flowering. Grass was harvested on a similar rotation to the grazing of the adjacent paddock. No fertiliser N was applied to any treatment and no urine/dung was applied.
- All leachate from each lysimeter was collected and sampled periodically for leachate volume, ammonium-N ($\text{NH}_4\text{-N}$), nitrate-N/nitrite-N ($\text{NO}_x\text{-N}$), total N, total dissolved carbon, dissolved inorganic carbon, dissolved organic carbon, reactive P, and total P.

Results

- There was no significant difference in the mass of N leaching between the lucerne with and without the topsoil amended with biochar.
- Total nitrogen leached from lysimeters cultivated and planted with lucerne averaged 4.6 kg/ ha/yr over years 1 – 4. This was significantly higher than leaching from the established ryegrass/clover pasture where the average was 1.6 kg N/ha/yr.
- Higher average N leaching from lucerne than ryegrass/clover was due to a pulse of N in year 2 (13.4 kg/ha). This was likely due to cultivation, because there was no N pulse in lysimeters with established ryegrass/clover pasture (which were not cultivated).
- Although there was a significant difference in leaching between ryegrass and lucerne treatments for year 2, there was no significant difference in leaching for any other year.

- Lucerne extracted more soil water than ryegrass/clover pasture, and hence drainage volumes were lower.

Conclusions

- Addition of biochar did not significantly affect N leaching under lucerne in this study, and is therefore not recommended (at the rate used) as a practice to reduce N leaching under lucerne on these pumice soils (although there may be other benefits).
- Average annual N leaching from lucerne was 4.6 kg/ha/yr. This was significantly higher than the ryegrass/clover pasture (1.6 kg/ha/yr).
- The only major difference in N leaching between lucerne and rye/pasture was in year 2, presumably due to cultivation. The magnitude of this 'cultivation' effect on the long-term average N leaching would depend on the longevity of the lucerne crop (e.g. if the crop lasts 10 years, expected average N leaching would be lower).
- Despite average N leaching under lucerne being higher than under ryegrass/clover, it was still considerably lower than the value of 19 kg/ha currently assigned by Waikato Regional Council. Therefore the value should be reviewed.

1 Introduction

This is the final report to Taupō Lake Care Inc. (TLC) and the Ministry for Primary Industries under Grant No 13/059 in relation to nitrogen (N) leaching under cut-and-carry lucerne grown in large diameter lysimeters at Tihoi. The report covers leachate collected during the period from 2011 to 2015.

2 Background

Lake Taupō Protection Trust (LTPT) and the Sustainable Farming Fund (SFF) have funded a 4-year field trial on N-leaching under cut-and-carry lucerne on a TLC member's Tihoi farm (Fig. 1). At this site an underground facility is used to collect leachate from large diameter lysimeters. The leaching data will be used by the Overseer[®] Committee to update the lucerne module within Overseer[®].



Figure 1 Lysimeter facility at Tihoi showing lucerne in the foreground and ryegrass/clover pasture in the background. Also visible are webcam, solar panels, cell phone aerial, rain gauges, roof of underground facility, and storage shed.

3 Objective

To quantify N-leaching from lysimeters cultivated and planted with lucerne, or lucerne with topsoil amended with 10 t/ha biochar and established ryegrass/clover.

4 Methods

A lysimeter facility at Tihoi (Fig. 2) was established and contained large lysimeters (1 m diameter \times 1.5 m high) planted with (1) lucerne, or (2) lucerne with topsoil amended with 10 t/ha biochar, or (3) existing undisturbed ryegrass/clover pasture. There were four replicate lysimeters for each treatment. The lysimeters were collected nearby from established pasture, and the two lucerne treatments were cultivated before lucerne seeds were sown at a rate of 120 per square metre. Lysimeters containing ryegrass/clover were extracted from established pasture grass and not cultivated.



Figure 2 Lysimeter facility at Tihoi under construction.

Before the spring lucerne growing season a 150-mm-deep soil sample was obtained from each lysimeter by tube-type soil corer and bulked by treatment. The soil samples were sent to Hills Laboratories for analysis and the results forwarded to Genetic Technologies for fertiliser recommendation for each treatment. N was not included in any of the fertiliser applications.

Lucerne was harvested (cut and carry) at approximately 10% flowering (Fig. 3). The grass was harvested on a similar rotation to the grazing of the adjacent paddock



Figure 3 Lucerne ready for harvest.

Leachate was collected into 200-L barrels and sampled periodically based on volume collected and anticipated weather conditions. Before determining collected leachate volume, a 50-mL aliquot was subsampled for analyses of ammonium-N ($\text{NH}_4\text{-N}$), nitrate-N/nitrite-N ($\text{NO}_x\text{-N}$), total N, total dissolved carbon, dissolved inorganic carbon, dissolved organic carbon, reactive P, and total P. Analyses were conducted at the Landcare Research Environmental Chemistry Laboratory, which has International Accreditation New Zealand (IANZ) status. Test numbers used were 310, 314, 316, and details can be found at: <http://www.landcareresearch.co.nz/resources/laboratories/environmental-chemistry-laboratory/services/water-testing/methods-water#310>



Figure 4 Leachate collection barrels in the underground facility.

Reported concentrations, in milligrams per litre (mg/L), of analyte in the leachate were converted to kg/ha based on the volume of leachate and the area of the lysimeter. Leachate volume was also expressed as pore volumes (PV). A pore volume (648.5 L) is the amount of air (pores) in the soil, and is about 70% of the total volume of the soil core. Using PV allows comparison of data across different soils.

5 Results

This report gives the results for the 2011 – 2015 period. However note that the 2015 leaching period is incomplete – drainage was still occurring at the time of writing.

Table 3 in Appendix A shows all data for leachate collections between 2011 and 2015 and these data are also shown graphically in Figures B1–B6 in Appendix B. Appendix C, D, and E are included only to inform Overseer® modelling. Appendix C shows 9 am air and soil temperature for the 2011–2014 period at the lysimeter facility, Tihoi. Appendix D shows rainfall for the 2011–2014 period at the lysimeter facility, Tihoi. Appendix E gives soil physical properties at the lysimeter site.

During the first year, the N concentration in leachate from lysimeter 6 in the ryegrass/clover treatment was considerably higher than any of the other lysimeters. This was likely a result of a cattle urine patch, because the lysimeters were collected from a grazed paddock approximately 2 weeks after grazing. Thus lysimeter 6 has not been used in the calculations and graphs of total N leached. Lysimeters 5 (ryegrass/clover) and 8 (lucerne with biochar) started to show low volumes of leachate, and this was attributed to a leaky joint. The lysimeters were extracted and possible leaky joints repaired. Leachate volumes for lysimeters 5 and 8 have been recalculated as the average from the other three lysimeters within the treatment.

Over the 2011–2015 period, each leachate volume collected under lucerne-planted lysimeters and ryegrass/clover-planted lysimeters ranged from c. 0 to 130 L. The total volume collected since the start of the trial was c. 1370–1730L or c. 2.0–2.7 PV. Total leachate volume was lower from the lysimeters cultivated and planted with lucerne (1286 L) than those in established ryegrass/clover pasture (1551 L). The N concentration in leachate from lucerne-planted lysimeters ranged from c. 0 to 6.45 mg/L, and from c. 0.00 to c. 3.07 mg/L in leachate from ryegrass/clover lysimeters. The total mass of N in leachate at each collection ranged from c. 0.00 to 9.06 kg/ha in the lysimeters planted with lucerne, and c. 0.00 to 2.93 kg/ha in leachate from lysimeters containing ryegrass/clover. There were no significant differences in total N leaching between the lucerne and lucerne + biochar lysimeters, and therefore these two treatments were grouped for reporting of mean leaching values.

In year 1, total N leaching was low (2.6 kg/ha) and did not differ between treatments (Figure 5, Tables 1 & 2). In year 2, the N concentration in leachate and total N leaching increased considerably in the lysimeters planted with lucerne (13.4 kg/ha), and was significantly higher than from the ryegrass/clover lysimeters (2.0 kg/ha). By year 3, N leaching had declined in the lysimeters planted with lucerne (< 3.0 kg/ha) and was again not significantly different from the ryegrass/clover lysimeters. N leaching remained low in year 4, and again there was no significant difference in N leaching between treatments. Averaged over the 4 years, N leaching was 4.6 kg/ha from the lucerne lysimeters and this was significantly higher than from the ryegrass/clover lysimeters (1.6 kg/ha, Fig. 5 Tables 1 & 2).

Table 1 Total N leached each year under lysimeters cultivated and planted with lucerne

Lysimeter number	N leached kg/ha								Average
	1B	2B	5B	9B	3L	4L	7L	10L	
Year 1	0.61	1.13	1.23	1.03	0.29	1.21	5.04	0.98	1.44
Year 2	9.44	11.05	7.9	21.55	11.24	20.34	17.76	7.93	13.40
Year 3	2.33	3.11	2.28	4.04	2.34	2.1	3.33	4.26	2.97
Year 4	0.97	0.56	0.88	0.03	0.97	0.46	0.67	0.66	0.65
Year 5*	0.15	0.3	0.25	0.47	0.13	0.11	0.51	0.2	0.27

* Not a full year

Table 2 Total N leached each year under lysimeters of established ryegrass/clover pasture

Lysimeter number	N leached kg/ha			Average
	8G	11G	12G	
Year 1	0.44	0.35	0.38	0.39
Year 2	0.81	1.19	0.26	0.75
Year 3	2.86	6.79	2.80	4.15
Year 4	0.52	2.11	0.79	1.14
Year 5*	0.17	0.45	0.16	0.26

* Not a full year

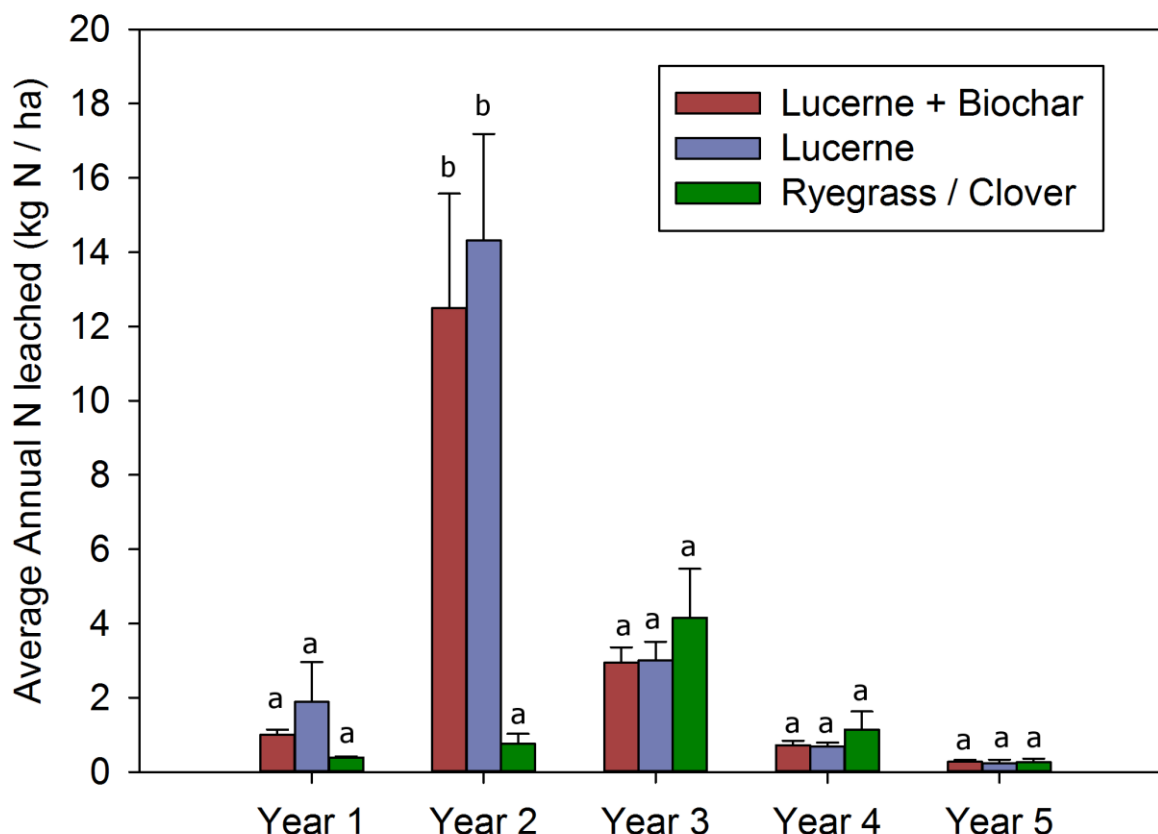


Figure 5 Total nitrogen leached from lysimeters cultivated and planted in lucerne and from lysimeters of established ryegrass/clover pasture. Error bars are from the data of the 4 lucerne lysimeters and 3 ryegrass/clover lysimeters. Note: for year 5, drainage was still occurring at the time of writing. Years with a are significantly different to years with b.

6 Discussion

There was no significant difference in the mass of N leaching from lysimeters sown with lucerne and those amended with 10 t/ha biochar in the top 150 mm then sown with lucerne. Because lucerne is a deep rooting crop and there were no urine returns, it was not surprising to have no significant treatment effect.

Average annual N leaching from lucerne was 4.6 kg/ha/yr, which was significantly higher than the ryegrass/clover pasture (1.6 kg/ha/yr). This difference was due to differences in year 2 when leaching was 13.4 kg/ha in lysimeters planted with lucerne, compared with only 2.0 kg/ha in the ryegrass/clover lysimeters (Fig. 5, Tables 2 & 3). The pulse of N leaching in year 2 was attributed to cultivation. The delay in N leaching (to year 2) in the lucerne lysimeters is consistent with the pore volume of the soil to 1.5 m, typical annual drainage volumes, and matrix flow which is expected in pumice soils.

Cultivation of the soil releases nitrogen (Francis et al. 1992) as plant material decomposes and plant uptake of nitrogen is reduced. Physical disruption of the soil may also bring microbes in contact with fresh previously unavailable substrate (Silgram & Shepherd 1999). The peaks were likely associated with cultivation before sowing lucerne and are absent from

the lysimeters planted in ryegrass/clover as the lysimeters were installed with the farm pasture grass intact and not cultivated.

It is possible that if the ryegrass/clover lysimeters were cultivated and re-sown to ryegrass/clover pasture, N leaching losses could have been greater than lucerne because the shallower rooting depth of pasture grass (and therefore less 'time' to capture N leaching down the profile). These N leaching values represent N leached at a depth of 1.5 m and cannot be compared with measurements made at 0.6 m. It is possible that as the lucerne roots were contained within the lysimeters, N uptake was higher than under field-grown conditions.

As urine (high in ammonium) is not added to the lysimeters the large majority of total N leached is in the form of nitrate/nitrite (NO_x) rather than ammonium (NH₄) (data not shown).

The relatively large mass of N leached in year 3 from lysimeters containing established ryegrass/clover pasture has not been determined, but may relate to a dry summer in the previous year.

Over the period from autumn year 2 to autumn year 5, the lucerne extracted nearly 430 L per lysimeter more water than the grass which is about 140 L per year over the 3 years. Lucerne has a much deeper rooting system than ryegrass/clover pasture and is thought to be extracting soil water from the older silty volcanic tephra (ash) below 90 cm which underlies the younger Taupō Pumice soil material (Fig. 6). This allows the lucerne to continue growing during summer when pastures dry out (Fig. 7). Analyses from other locations show the older silty volcanic tephra can store large amounts of plant available water.



Figure 6 Rooting pattern of lucerne around a lysimeter (a) and ryegrass/clover pasture in a nearby paddock (b). Note the older volcanic silty tephra below 90 cm in the undisturbed soil.



Figure 7 Webcam picture of lucerne in the foreground while pastures in the background have dried off.

7 Conclusions

- Addition of biochar (at 10 t/ha) did not significantly affect N leaching under lucerne in this study, and is therefore not recommended as a practice to reduce N leaching under lucerne on these pumice soils (there may be other benefits).
- Average annual N leaching from lucerne was 4.6 kg/ha/yr. This was significantly higher than the ryegrass/clover pasture (1.6 kg/ha/yr).
- The only major difference in N leaching between lucerne and rye/pasture was in year 2, presumably due to cultivation. The magnitude of this ‘cultivation’ effect on the long-term average N leaching would depend on the longevity of the lucerne crop (e.g. if the crop lasts 10 years, expected average N leaching would be lower).
- Despite average N leaching under lucerne being higher than under ryegrass/clover, it was still considerably lower than the value of 19 kg/ha currently assigned by Waikato Regional Council. Therefore the value should be reviewed.

8 Acknowledgements

This research is supported financially by LTPT and SFF through TLC. Ballance Agri-Nutrients Limited supplies the fertiliser for the trial. Pioneer Seeds supplied the lucerne seed and Genetic Technologies interprets soil and foliage test results for fertiliser recommendations. Farm owners Mike and Sharon Barton continue to provide ongoing enthusiastic support for the project.

9 References

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- Silgram M, Shepherd MA 1999. The effects of cultivation on soil nitrogen mineralization. *Advances in Agronomy* 65: 267–297.

Appendix A – Lysimeter leaching data, 2011 - 2015

Table 3 Lysimeter leaching data for the 2011 to 2015 period. The lysimeters are tagged L for lucerne, B for lucerne with biochar in the topsoil, and G for ryegrass/clover

	Date	Lysimeter number											
		3L	4L	7L	10L	1B	2B	5B	9B	6G	8G	11G	12G
Volume of leachate in collection barrel (L)	24/07/2011	144.2	151.9	141.85	147.6	149.2	126.6	143.05	154.5	146.2	149.87	154.2	149.2
	21/09/2011	45.9	48.9	39.4	42.9	50.4	44.2	39.1	48.9	36.9	41.70	45.3	42.9
	5/11/2011	72.49	76.44	70.64	73.39	72.24	72.3	66.24	80.72	72.3	70.34	71.54	67.17
	14/12/2011	23.78	15.53	21.58	22.68	23.08	13	17.6	27.27	12.05	15.20	15	18.56
	11/01/2012	57.46	56.56	60.54	56.16	42.36	47.86	46.16	49.86	30.08	34.41	35.68	37.48
	1/02/2012	26.98	29.68	23.98	24.68	25.68	25.43	20.38	21.18	36.18	36.78	37.48	36.68
	25/05/2012	44.16	58.46	43.06	41.36	35.08	46.56	25.88	45.96	58.36	67.91	70.84	74.54
	20/07/2012	102.3	106.5	110.9	114.5	108.1	111.7	74.74	116.8	112.4	113.40	110.6	117.2
	26/08/2012	124.08	113	122.18	123.08	124.88	126.88	103.5	131.68	127.08	126.58	122.18	130.48
	14/10/2012	86.82	71.74	80.44	83.42	89.52	88.42	59.66	90.12	89.07	89.70	86.12	93.92
	17/11/2012	33	26	29.85	31.1	30.8	33.3	15.7	36	40.6	41.57	41.5	42.6
	20/06/2013	20.47	36.67	23.47	15.6	17.4	15.6	12.1	23.47	101.55	108.43	118.25	105.5
	28/07/2013	69.31	68.36	72.21	71.31	73.61	71.71	52.54	72.21	66.71	66.81	63.01	70.71
	24/09/2013	90.18	80	92.18	91.78	88.88	91.08	61.81	89.28	101.68	98.27	91.28	101.85
	31/10/2013	83.28	75.5	43.64	82.93	81.18	84.88	47.84	77.01	79.11	80.73	80	83.08
	29/11/2013	9.2	10.5	10	11.4	8	13.3	7.3	1	29.77	28.80	24.17	32.47
	19/12/2013	37.2	42.2	43.9	43.3	25.7	44.5	42.8	13.6	38.5	39.63	36	44.4
	31/01/2014	0	0	0	0	0	0	0	0	4.6	0.00	0.95	3.5
	28/06/2014	0	25.47	5.1	9	4.5	0.9	0.65	4.9	84.78	78.11	71.61	80.68
	31/07/2014	79.7	81.2	81.8	74.8	73.5	74	78	78.7	84.2	87.30	82.2	85.9
	28/08/2014	70.2	62.7	67.2	68.4	60.5	68.2	65	66.3	68.5	70.10	69.3	69.5
	30/09/2014	48.4	41.4	47.3	46.8	36.8	43.5	43.5	43.6	50.28	48.90	43.92	48
	28/10/2014	14	14.5	13.5	11.8	7.7	13.5	22.8	14.3	26.9	28.90	22.8	26.9
	28/11/2014	20.17	12.8	14	10	10.5	20.17	20.17	34.5	33.6	21.80	28.1	33.17
	29/12/2014	0.08	0.08	0.08	0.06	0.06	0.08	0.15	4.9	5.8	0.18	1.1	3.5
	2/06/2015	0	0.5	0	0	3	2.2	2.1	0	53.9	43.30	44.4	28.77
7/07/2015	60.5	85.9	81	62	90.2	88.9	86.9	81.7	97.4	101.40	95	100.85	

	Date	Lysimeter number											
		3L	4L	7L	10L	1B	2B	5B	9B	6G	8G	11G	12G
Cumulative volume of leachate (L)	24/07/2011	144.2	151.9	141.85	147.6	149.2	126.6	143.43	154.5	146.2	149.87	154.2	149.2
	21/09/2011	190.1	200.8	181.25	190.5	199.6	170.8	191.26	203.4	183.1	191.57	199.5	192.1
	5/11/2011	262.59	277.24	251.89	263.89	271.84	243.1	266.35	284.12	255.4	261.90	271.04	259.27
	14/12/2011	286.37	292.77	273.47	286.57	294.92	256.1	287.47	311.39	267.45	277.11	286.04	277.83
	11/01/2012	343.83	349.33	334.01	342.73	337.28	303.96	334.16	361.25	297.53	311.52	321.72	315.31
	1/02/2012	370.81	379.01	357.99	367.41	362.96	329.39	358.26	382.43	333.71	348.30	359.2	351.99
	25/05/2012	414.97	437.47	401.05	408.77	398.04	375.95	400.79	428.39	392.07	416.21	430.04	426.53
	20/07/2012	517.27	543.97	511.95	523.27	506.14	487.65	512.99	545.19	504.47	529.61	540.64	543.73
	26/08/2012	641.35	656.97	634.13	646.35	631.02	614.53	640.80	676.87	631.55	656.19	662.82	674.21
	14/10/2012	728.17	728.71	714.57	729.77	720.54	702.95	730.16	766.99	720.62	745.90	748.94	768.13
	17/11/2012	761.17	754.71	744.42	760.87	751.34	736.25	763.52	802.99	761.22	787.46	790.44	810.73
	20/06/2013	781.64	791.38	767.89	776.47	768.74	751.85	782.35	826.46	862.77	895.90	908.69	916.23
	28/07/2013	850.95	859.74	840.1	847.78	842.35	823.56	854.86	898.67	929.48	962.71	971.7	986.94
	24/09/2013	941.13	939.74	932.28	939.56	931.23	914.64	944.60	987.95	1031.16	1060.98	1062.98	1088.79
	31/10/2013	1024.41	1015.24	975.92	1022.49	1012.41	999.52	1025.63	1064.96	1110.27	1141.71	1142.98	1171.87
	29/11/2013	1033.61	1025.74	985.92	1033.89	1020.41	1012.82	1033.06	1065.96	1140.04	1170.51	1167.15	1204.34
	19/12/2013	1070.81	1067.94	1029.82	1077.19	1046.11	1057.32	1060.99	1079.56	1178.54	1210.14	1203.15	1248.74
	31/01/2014	1070.81	1067.94	1029.82	1077.19	1046.11	1057.32	1060.99	1079.56	1183.14	1210.14	1204.1	1252.24
	28/06/2014	1070.81	1093.41	1034.92	1086.19	1050.61	1058.22	1064.43	1084.46	1267.92	1288.25	1275.71	1332.92
	31/07/2014	1150.51	1174.61	1116.72	1160.99	1124.11	1132.22	1139.83	1163.16	1352.12	1375.55	1357.91	1418.82
	28/08/2014	1220.71	1237.31	1183.92	1229.39	1184.61	1200.42	1204.83	1229.46	1420.62	1445.65	1427.21	1488.32
	30/09/2014	1269.11	1278.71	1231.22	1276.19	1221.41	1243.92	1246.13	1273.06	1470.9	1494.55	1471.13	1536.32
	28/10/2014	1283.11	1293.21	1244.72	1287.99	1229.11	1257.42	1257.96	1287.36	1497.8	1523.45	1493.93	1563.22
	28/11/2014	1303.28	1306.01	1258.72	1297.99	1239.61	1277.59	1279.68	1321.86	1531.4	1545.25	1522.03	1596.39
	29/12/2014	1303.36	1306.09	1258.8	1298.05	1239.67	1277.67	1281.36	1326.76	1537.2	1545.43	1523.13	1599.89
	2/06/2015	1303.36	1306.59	1258.8	1298.05	1242.67	1279.87	1283.10	1326.76	1591.1	1588.73	1567.53	1628.66
	7/07/2015	1363.86	1392.49	1339.8	1360.05	1332.87	1368.77	1370.03	1408.46	1688.5	1690.13	1662.53	1729.51

	Date	Lysimeter number											
		3L	4L	7L	10L	1B	2B	5B	9B	6G	8G	11G	12G
Cumulative pore volume of leachate	24/07/2011	0.22	0.23	0.22	0.23	0.23	0.20	0.22	0.24	0.23	0.23	0.24	0.23
	21/09/2011	0.29	0.31	0.28	0.29	0.31	0.26	0.29	0.31	0.28	0.30	0.31	0.30
	5/11/2011	0.40	0.43	0.39	0.41	0.42	0.37	0.41	0.44	0.39	0.40	0.42	0.40
	14/12/2011	0.44	0.45	0.42	0.44	0.45	0.39	0.44	0.48	0.41	0.43	0.44	0.43
	11/01/2012	0.53	0.54	0.52	0.53	0.52	0.47	0.52	0.56	0.46	0.48	0.50	0.49
	1/02/2012	0.57	0.58	0.55	0.57	0.56	0.51	0.55	0.59	0.51	0.54	0.55	0.54
	25/05/2012	0.64	0.67	0.62	0.63	0.61	0.58	0.62	0.66	0.60	0.64	0.66	0.66
	20/07/2012	0.80	0.84	0.79	0.81	0.78	0.75	0.79	0.84	0.78	0.82	0.83	0.84
	26/08/2012	0.99	1.01	0.98	1.00	0.97	0.95	0.99	1.04	0.97	1.01	1.02	1.04
	14/10/2012	1.12	1.12	1.10	1.13	1.11	1.08	1.13	1.18	1.11	1.15	1.15	1.18
	17/11/2012	1.17	1.16	1.15	1.17	1.16	1.14	1.18	1.24	1.17	1.21	1.22	1.25
	20/06/2013	1.21	1.22	1.18	1.20	1.19	1.16	1.21	1.27	1.33	1.38	1.40	1.41
	28/07/2013	1.31	1.33	1.30	1.31	1.30	1.27	1.32	1.39	1.43	1.48	1.50	1.52
	24/09/2013	1.45	1.45	1.44	1.45	1.44	1.41	1.46	1.52	1.59	1.64	1.64	1.68
	31/10/2013	1.58	1.57	1.50	1.58	1.56	1.54	1.58	1.64	1.71	1.76	1.76	1.81
	29/11/2013	1.59	1.58	1.52	1.59	1.57	1.56	1.59	1.64	1.76	1.80	1.80	1.86
	19/12/2013	1.65	1.65	1.59	1.66	1.61	1.63	1.64	1.66	1.82	1.87	1.86	1.93
	31/01/2014	1.65	1.65	1.59	1.66	1.61	1.63	1.64	1.66	1.82	1.87	1.86	1.93
	28/06/2014	1.65	1.69	1.60	1.67	1.62	1.63	1.64	1.67	1.96	1.99	1.97	2.06
	31/07/2014	1.77	1.81	1.72	1.79	1.73	1.75	1.76	1.79	2.08	2.12	2.09	2.19
	28/08/2014	1.88	1.91	1.83	1.90	1.83	1.85	1.86	1.90	2.19	2.23	2.20	2.30
	30/09/2014	1.96	1.97	1.90	1.97	1.88	1.92	1.92	1.96	2.27	2.30	2.27	2.37
	28/10/2014	1.98	1.99	1.92	1.99	1.90	1.94	1.94	1.99	2.31	2.35	2.30	2.41
	28/11/2014	2.01	2.01	1.94	2.00	1.91	1.97	1.97	2.04	2.36	2.38	2.35	2.46
	29/12/2014	2.01	2.01	1.94	2.00	1.91	1.97	1.98	2.05	2.37	2.38	2.35	2.47
	2/06/2015	2.01	2.01	1.94	2.00	1.92	1.97	1.98	2.05	2.45	2.45	2.42	2.51
7/07/2015	2.10	2.15	2.07	2.10	2.06	2.11	2.11	2.17	2.60	2.61	2.56	2.67	

	Date	Lysimeter number											
		3L	4L	7L	10L	1B	2B	5B	9B	6G	8G	11G	12G
Total N in leachate (mg/L)	24/07/2011	0.032	0.149	0.260	0.212	0.054	0.095	0.158	0.083	4.791	0.062	0.020	0.054
	21/09/2011	0.056	0.128	0.618	0.150	0.104	0.156	0.177	0.152	2.993	0.111	0.084	0.090
	5/11/2011	0.051	0.192	0.845	0.122	0.102	0.327	0.282	0.167	2.483	0.102	0.098	0.075
	14/12/2011	0.028	0.305	1.658	0.117	0.243	0.222	0.206	0.375	2.348	0.057	0.147	0.047
	11/01/2012	0.065	0.257	1.628	0.107	0.159	0.308	0.239	0.249	1.823	0.074	0.090	0.045
	1/02/2012	0.086	0.365	2.165	0.197	0.161	0.360	0.317	0.294	1.730	0.071	0.062	0.095
	25/05/2012	0.324	0.413	2.091	0.165	0.210	0.306	0.240	0.357	1.253	0.173	0.269	0.075
	20/07/2012	0.641	0.446	1.781	0.155	0.283	0.241	0.275	0.427	1.003	0.071	0.151	0.020
	26/08/2012	2.430	3.975	2.910	1.320	1.365	1.965	0.863	3.840	0.590	0.020	0.173	0.020
	14/10/2012	3.080	7.685	4.490	3.185	3.260	3.485	2.750	6.455	0.638	0.048	0.120	0.044
	17/11/2012	1.053	6.354	2.544	0.957	2.394	2.199	2.604	4.359	0.564	0.555	0.134	0.026
	20/06/2013	0.330	0.239	0.644	0.524	0.461	0.417	0.491	0.639	0.545	0.107	0.333	0.126
	28/07/2013	0.069	0.096	0.066	0.054	0.066	0.072	0.043	0.069	0.519	0.061	0.196	0.034
	24/09/2013	1.381	1.336	1.321	1.340	1.349	1.421	1.318	1.313	1.751	1.339	1.571	1.180
	31/10/2013	0.059	0.039	1.334	1.369	0.058	0.041	0.049	1.382	0.500	0.067	1.886	0.092
	29/11/2013	0.122	0.107	0.197	0.242	0.242	0.107	0.107	0.422	0.632	0.437	0.932	0.272
	19/12/2013	0.020	0.030	0.020	0.180	0.105	0.975	0.120	0.120	0.510	0.225	1.215	0.285
	31/01/2014	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.135	0.000	0.600	1.485
	28/06/2014	0.299	0.194	1.476	0.633	0.458	1.322	2.811	0.719	0.449	0.092	0.684	0.096
	31/07/2014	0.100	0.090	0.177	0.129	0.111	0.114	0.202	0.085	0.243	0.141	0.460	0.085
	28/08/2014	0.435	0.108	0.118	0.141	0.409	0.139	0.160	0.103	0.189	0.105	0.331	0.220
	30/09/2014	0.403	0.197	0.047	0.267	0.570	0.252	0.229	0.088	0.045	0.057	0.269	0.113
	28/10/2014	0.020	0.042	0.501	0.089	0.217	0.055	0.357	0.065	0.343	0.051	0.102	0.294
	28/11/2014	0.031	0.020	0.127	0.147	0.119	0.167	0.127	0.130	0.130	0.024	0.146	0.110
	29/12/2014	0.354	0.351	1.119	0.983	0.337	1.035	0.976	0.522	0.350	0.127	0.230	0.217
	2/06/2015	0.000	0.329	0.000	0.000	0.368	0.953	0.749	0.000	0.024	0.054	0.134	0.020
7/07/2015	0.128	0.075	0.383	0.199	0.091	0.150	0.106	0.287	0.100	0.079	0.228	0.088	

	Date	Lysimeter number											
		3L	4L	7L	10L	1B	2B	5B	9B	6G	8G	11G	12G
Total N in leachate (kg/ha)	24/07/2011	0.075	0.371	0.605	0.513	0.132	0.197	0.371	0.210	11.517	0.152	0.051	0.132
	21/09/2011	0.042	0.103	0.400	0.106	0.086	0.113	0.139	0.122	1.816	0.076	0.063	0.063
	5/11/2011	0.061	0.241	0.981	0.147	0.121	0.389	0.348	0.221	2.951	0.118	0.115	0.083
	14/12/2011	0.011	0.078	0.588	0.044	0.092	0.047	0.071	0.168	0.465	0.014	0.036	0.014
	11/01/2012	0.061	0.239	1.620	0.098	0.111	0.242	0.183	0.204	0.901	0.042	0.053	0.028
	1/02/2012	0.038	0.178	0.854	0.080	0.068	0.151	0.126	0.103	1.029	0.043	0.038	0.057
	25/05/2012	0.235	0.396	1.480	0.112	0.121	0.234	0.168	0.270	1.202	0.193	0.313	0.092
	20/07/2012	1.079	0.782	3.248	0.293	0.503	0.442	0.508	0.820	1.853	0.133	0.274	0.039
	26/08/2012	4.957	7.385	5.846	2.671	2.803	4.099	1.815	8.314	1.232	0.042	0.347	0.043
	14/10/2012	4.396	9.064	5.938	4.368	4.798	5.066	4.039	9.564	0.934	0.071	0.170	0.067
	17/11/2012	0.571	2.716	1.249	0.489	1.212	1.204	1.428	2.580	0.376	0.379	0.091	0.018
	20/06/2013	0.111	0.144	0.248	0.134	0.132	0.107	0.152	0.247	0.910	0.190	0.648	0.219
	28/07/2013	0.078	0.108	0.078	0.063	0.080	0.085	0.051	0.082	0.569	0.067	0.203	0.039
	24/09/2013	2.048	1.757	2.002	2.023	1.972	2.129	1.945	1.928	2.928	2.163	2.358	1.976
	31/10/2013	0.081	0.049	0.957	1.867	0.077	0.057	0.065	1.750	0.651	0.089	2.481	0.126
	29/11/2013	0.018	0.018	0.032	0.045	0.032	0.023	0.013	0.007	0.309	0.207	0.370	0.145
	19/12/2013	0.012	0.021	0.014	0.128	0.044	0.713	0.055	0.027	0.323	0.147	0.719	0.208
	31/01/2014	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.010	0.000	0.009	0.085
	28/06/2014	0.000	0.081	0.124	0.094	0.034	0.020	0.159	0.058	0.625	0.118	0.805	0.127
	31/07/2014	0.131	0.120	0.237	0.158	0.134	0.138	0.251	0.110	0.336	0.202	0.622	0.120
	28/08/2014	0.502	0.111	0.131	0.158	0.407	0.156	0.171	0.113	0.213	0.121	0.378	0.252
	30/09/2014	0.321	0.134	0.036	0.205	0.345	0.180	0.155	0.063	0.037	0.046	0.194	0.089
	28/10/2014	0.005	0.010	0.111	0.017	0.027	0.012	0.069	0.015	0.152	0.024	0.038	0.130
	28/11/2014	0.010	0.004	0.029	0.024	0.020	0.055	0.045	0.073	0.072	0.009	0.067	0.060
	29/12/2014	0.000	0.000	0.001	0.001	0.000	0.001	0.027	0.042	0.033	0.000	0.004	0.012
	2/06/2015	0.000	0.005	0.000	0.000	0.022	0.085	0.100	0.000	0.021	0.039	0.098	0.009
7/07/2015	0.128	0.105	0.511	0.202	0.136	0.219	0.151	0.386	0.162	0.132	0.357	0.143	

	Date	Lysimeter number											
		3L	4L	7L	10L	1B	2B	5B	9B	6G	8G	11G	12G
Cumulative total N in leachate (kg/ha)	24/07/2011	0.075	0.371	0.605	0.513	0.132	0.197	0.370	0.210	11.517	0.149	0.051	0.132
	21/09/2011	0.117	0.473	1.006	0.619	0.218	0.310	0.484	0.331	13.332	0.225	0.113	0.196
	5/11/2011	0.177	0.715	1.986	0.766	0.339	0.699	0.791	0.552	16.283	0.343	0.228	0.279
	14/12/2011	0.188	0.792	2.575	0.809	0.432	0.746	0.851	0.721	16.748	0.358	0.264	0.293
	11/01/2012	0.249	1.031	4.195	0.908	0.543	0.988	1.032	0.925	17.650	0.399	0.317	0.321
	1/02/2012	0.287	1.209	5.048	0.988	0.610	1.139	1.138	1.027	18.679	0.442	0.355	0.378
	25/05/2012	0.523	1.606	6.529	1.100	0.732	1.373	1.240	1.297	19.881	0.635	0.668	0.470
	20/07/2012	1.602	2.387	9.777	1.393	1.234	1.816	1.579	2.117	21.734	0.768	0.942	0.509
	26/08/2012	6.559	9.773	15.623	4.064	4.037	5.915	3.047	10.431	22.966	0.810	1.289	0.552
	14/10/2012	10.955	18.837	21.561	8.432	8.835	10.981	5.744	19.995	23.900	0.880	1.459	0.619
	17/11/2012	11.526	21.553	22.809	8.921	10.047	12.185	6.416	22.575	24.276	1.260	1.550	0.637
	20/06/2013	11.637	21.697	23.058	9.055	10.179	12.292	6.513	22.822	25.186	1.450	2.198	0.856
	28/07/2013	11.716	21.805	23.136	9.118	10.259	12.377	6.551	22.903	25.755	1.517	2.401	0.895
	24/09/2013	13.763	23.562	25.138	11.141	12.231	14.505	7.890	24.831	28.683	3.680	4.760	2.871
	31/10/2013	13.845	23.611	26.095	13.008	12.308	14.562	7.929	26.582	29.334	3.769	7.241	2.998
	29/11/2013	13.863	23.629	26.128	13.053	12.340	14.585	7.941	26.589	29.643	3.976	7.611	3.142
	19/12/2013	13.875	23.650	26.142	13.181	12.384	15.299	8.026	26.616	29.966	4.122	8.330	3.351
	31/01/2014	13.875	23.650	26.142	13.181	12.384	15.299	8.026	26.616	29.976	4.122	8.340	3.436
	28/06/2014	13.875	23.731	26.266	13.275	12.418	15.318	8.056	26.673	30.601	4.240	9.145	3.563
	31/07/2014	14.006	23.851	26.503	13.433	12.551	15.456	8.315	26.783	30.937	4.441	9.767	3.683
	28/08/2014	14.508	23.962	26.634	13.591	12.959	15.613	8.486	26.896	31.150	4.562	10.144	3.935
	30/09/2014	14.829	24.096	26.670	13.796	13.303	15.793	8.650	26.959	31.187	4.608	10.338	4.025
	28/10/2014	14.834	24.106	26.781	13.813	13.331	15.805	8.784	26.974	31.339	4.632	10.376	4.155
	28/11/2014	14.844	24.110	26.811	13.838	13.351	15.860	8.826	27.048	31.411	4.641	10.444	4.215
29/12/2014	14.844	24.111	26.812	13.839	13.352	15.862	8.829	27.090	31.444	4.641	10.448	4.227	
2/06/2015	14.844	24.116	26.812	13.839	13.374	15.947	8.951	27.090	31.465	4.680	10.546	4.237	
7/07/2015	14.972	24.221	27.323	14.041	13.510	16.166	9.102	27.476	31.627	4.8125	10.903	4.383	

	Date	Lysimeter number											
		3L	4L	7L	10L	1B	2B	5B	9B	6G	8G	11G	12G
Cumulative millimetres of drainage	24/07/2011	227	239	223	232	235	199	225	243	230	232	242	235
	21/09/2011	299	316	285	299	314	268	301	320	288	305	314	302
	5/11/2011	413	436	396	415	427	382	419	447	401	419	426	408
	14/12/2011	450	460	430	450	464	403	452	489	420	432	450	437
	11/01/2012	540	549	525	539	530	478	525	568	468	465	506	496
	1/02/2012	583	596	563	578	571	518	563	601	525	501	565	553
	25/05/2012	652	688	630	643	626	591	630	673	616	553	676	670
	20/07/2012	813	855	805	823	796	767	806	857	793	656	850	855
	26/08/2012	1008	1033	997	1016	992	966	1007	1064	993	814	1042	1060
	14/10/2012	1145	1145	1123	1147	1133	1105	1148	1206	1133	903	1177	1207
	17/11/2012	1196	1186	1170	1196	1181	1157	1200	1262	1197	935	1242	1274
	20/06/2013	1229	1244	1207	1221	1208	1182	1230	1299	1356	1038	1428	1440
	28/07/2013	1338	1351	1321	1333	1324	1295	1344	1413	1461	1082	1527	1551
	24/09/2013	1479	1477	1465	1477	1464	1438	1485	1553	1621	1171	1671	1711
	31/10/2013	1610	1596	1534	1607	1591	1571	1612	1674	1745	1250	1797	1842
	29/11/2013	1625	1612	1550	1625	1604	1592	1624	1676	1792	1269	1835	1893
	19/12/2013	1683	1679	1619	1693	1644	1662	1668	1697	1853	1304	1891	1963
	31/01/2014	1683	1679	1619	1693	1644	1662	1668	1697	1860	1902	1893	1968
	28/06/2014	1683	1719	1627	1707	1651	1663	1673	1705	1993	2025	2005	2095
	31/07/2014	1808	1846	1755	1825	1767	1780	1792	1828	2125	2162	2134	2230
	28/08/2014	1919	1945	1861	1932	1862	1887	1894	1933	2233	2272	2243	2339
	30/09/2014	1995	2010	1935	2006	1920	1955	1959	2001	2312	2349	2312	2415
	28/10/2014	2017	2033	1956	2025	1932	1976	1977	2024	2354	2395	2348	2457
	28/11/2014	2049	2053	1978	2040	1948	2008	2012	2078	2407	2429	2392	2509
	29/12/2014	2049	2053	1979	2040	1949	2008	2014	2085	2416	2429	2394	2515
	2/06/2015	2049	2054	1979	2040	1953	2012	2017	2085	2501	2497	2464	2560
7/07/2015	2144	2189	2106	2138	2095	2151	2154	2214	2654	2657	2613	2719	

Appendix B – Graphs of drainage and N leached

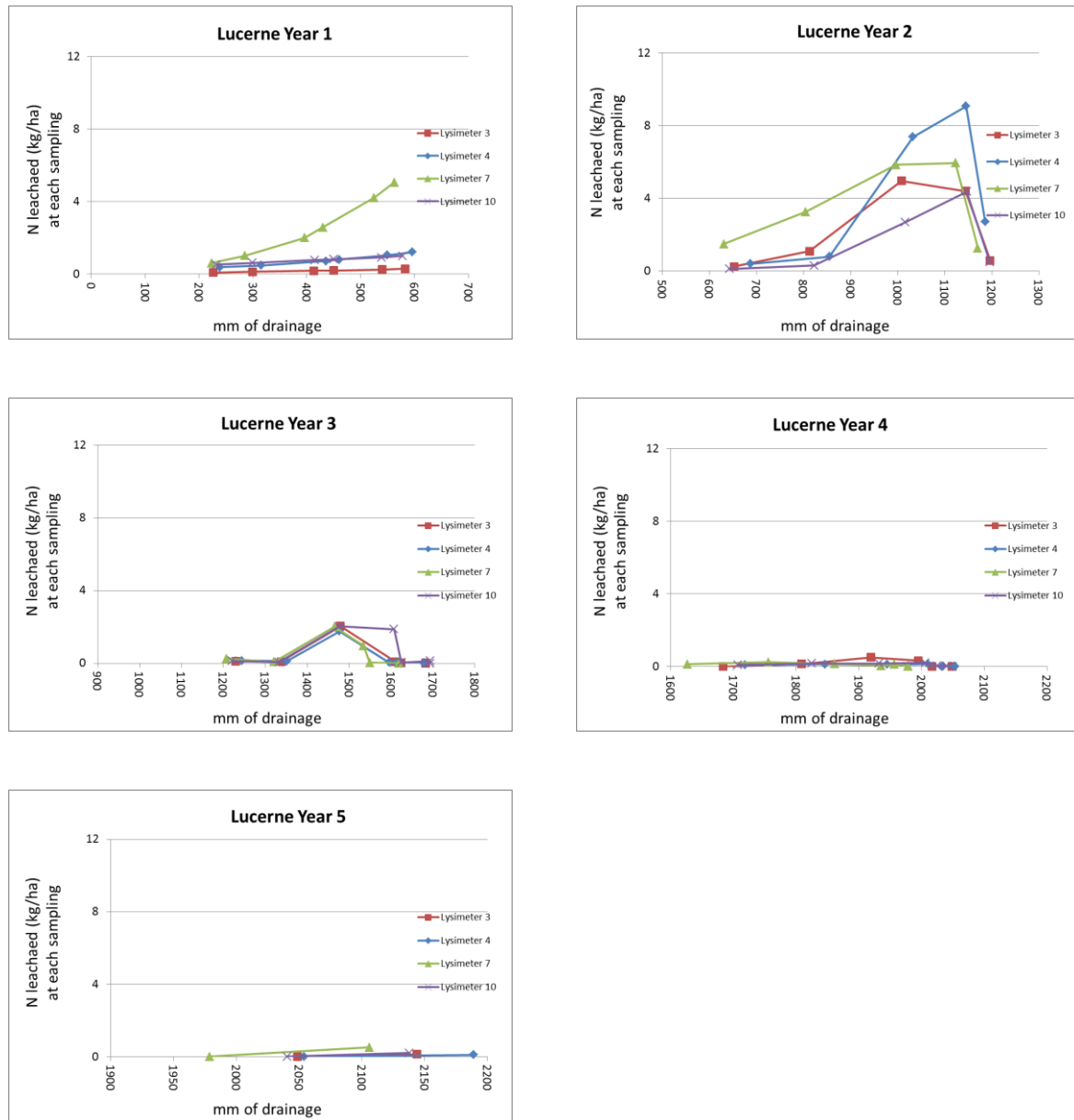


Figure 8 Cumulative drainage and N leached at each sampling from four replicated lysimeters cultivated and sown in lucerne. Each ‘year’ represents a drainage period, and specific dates were as follows: Year 1 = 24/07/11–01/02/12; Year 2 = 25/05/12–17/11/12; Year 3 = 20/06/13–31/01/14; Year 4 = 28/06/14–29/12/14; Year 5 = 02/06/15–07/07/15.

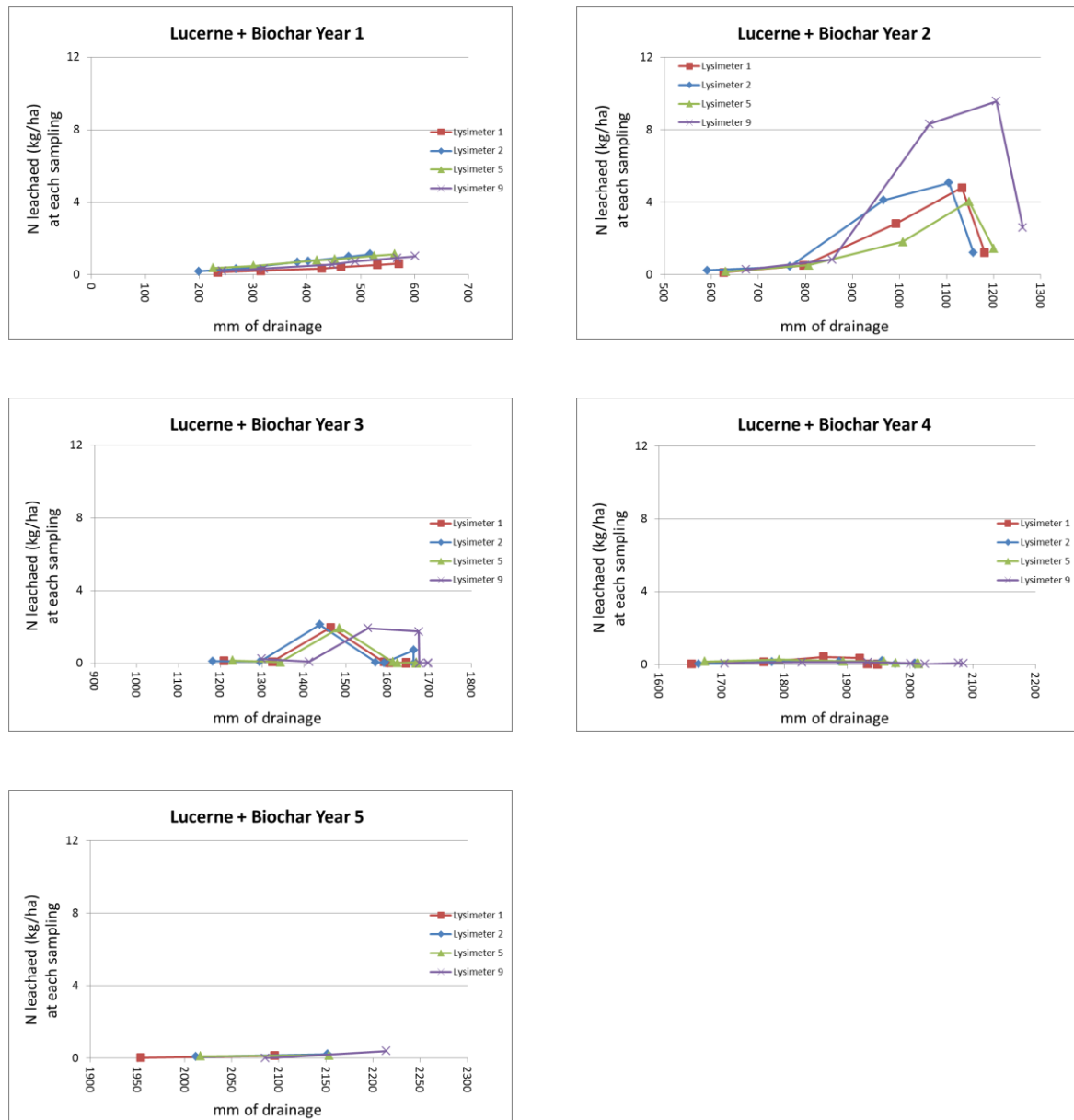


Figure 9 Drainage and N leached at each sampling from four replicated lysimeters cultivated and sown in lucerne amended with biochar. Each ‘year’ represents a drainage period, and specific dates were as follows: Year 1 = 24/07/11–01/02/12; Year 2 = 25/05/12–17/11/12; Year 3 = 20/06/13–31/01/14; Year 4 = 28/06/14–29/12/14; Year 5 = 02/06/15–07/07/15.

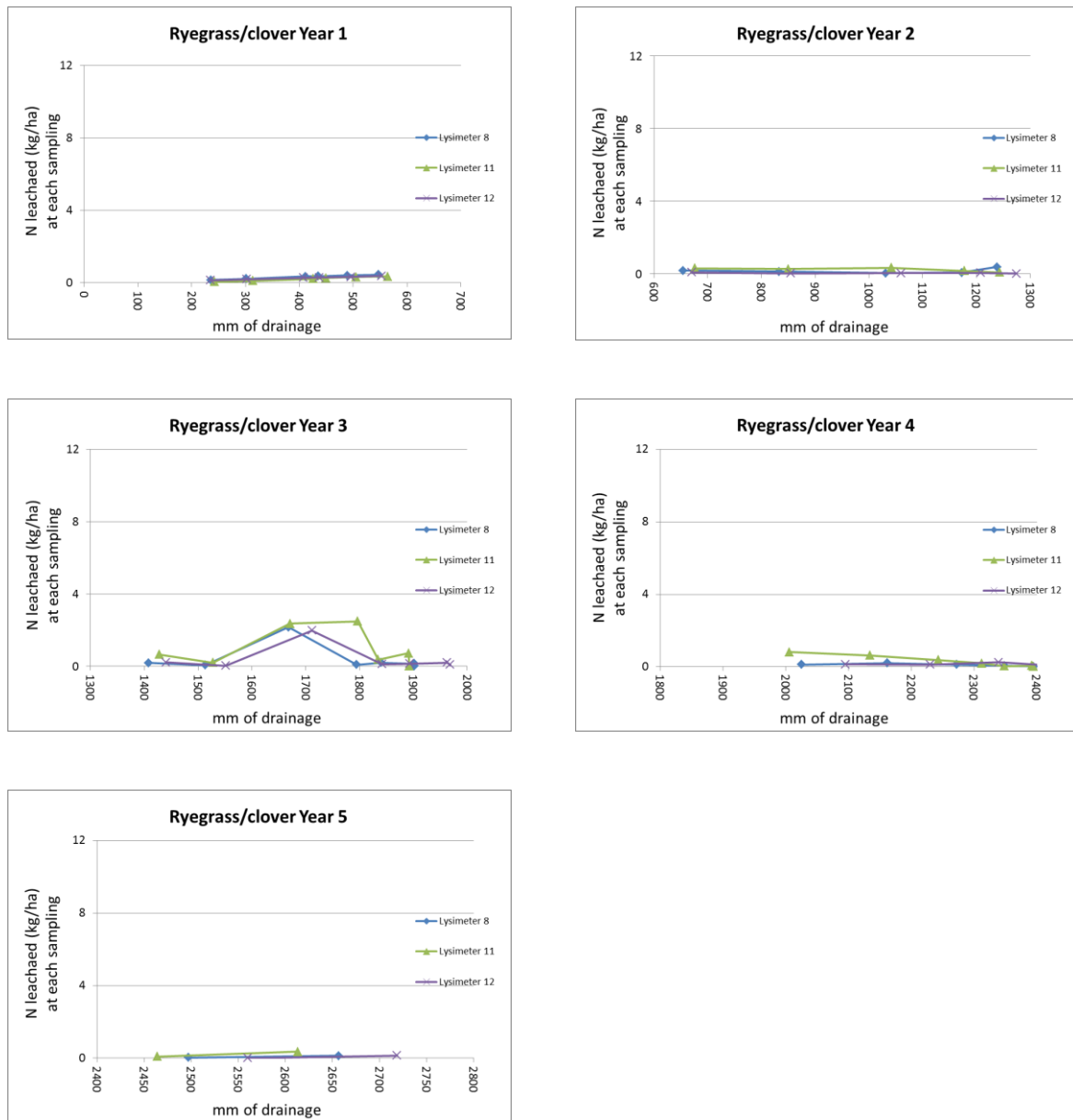


Figure 10 Drainage and N leached at each sampling from four replicated lysimeters from established ryegrass/clover pasture. Each ‘year’ represents a drainage period, and specific dates were as follows: Year 1 = 24/07/11–01/02/12; Year 2 = 25/05/12–17/11/12; Year 3 = 20/06/13–31/01/14; Year 4 = 28/06/14–29/12/14; Year 5 = 02/06/15–07/07/15.

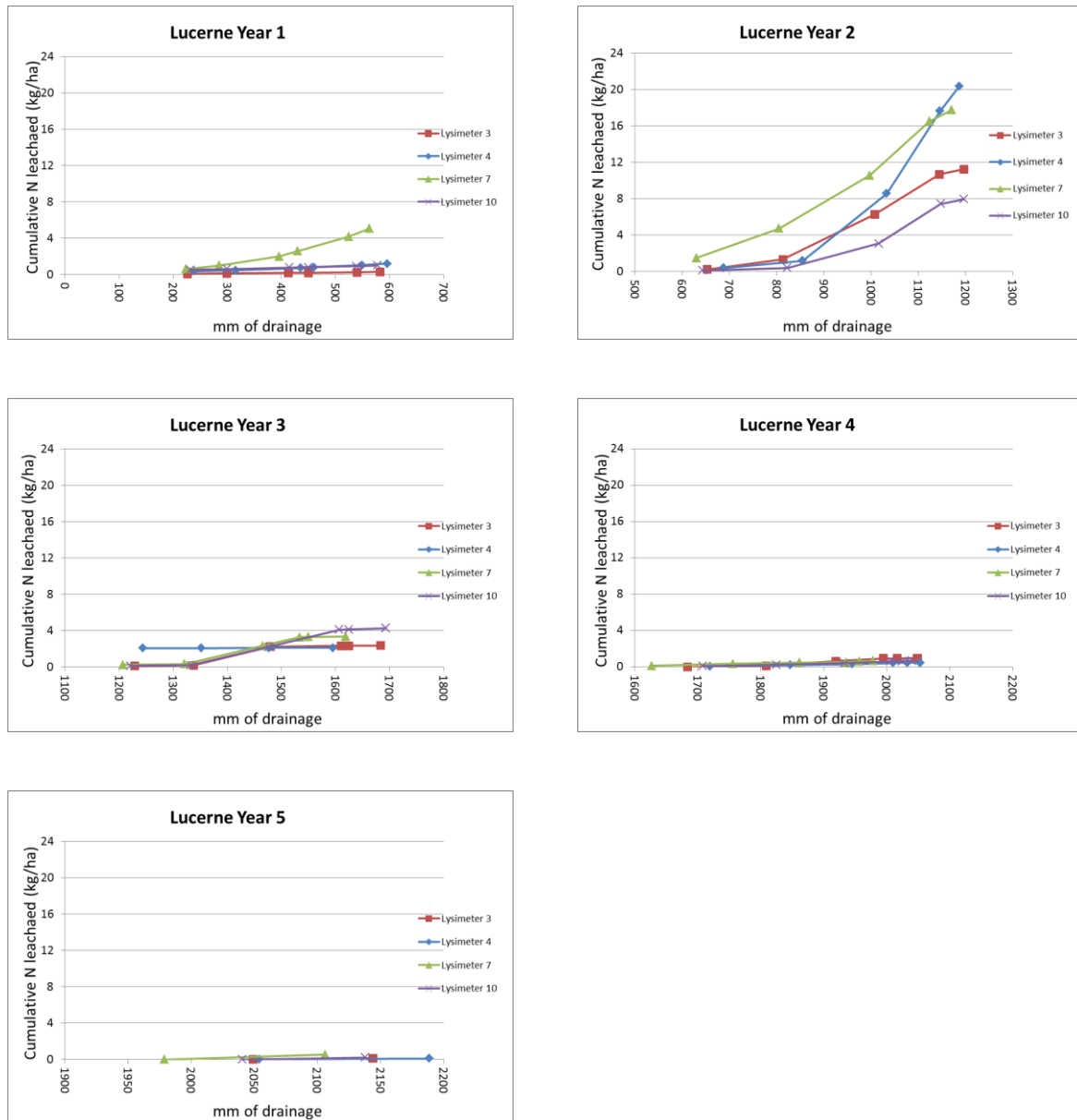


Figure 11 Drainage and cumulative N leached from four replicated lysimeters cultivated and sown in lucerne. Each 'year' represents a drainage period, and specific dates were as follows: Year 1 = 24/07/11–01/02/12; Year 2 = 25/05/12–17/11/12; Year 3 = 20/06/13–31/01/14; Year 4 = 28/06/14–29/12/14; Year 5 = 02/06/15–07/07/15.

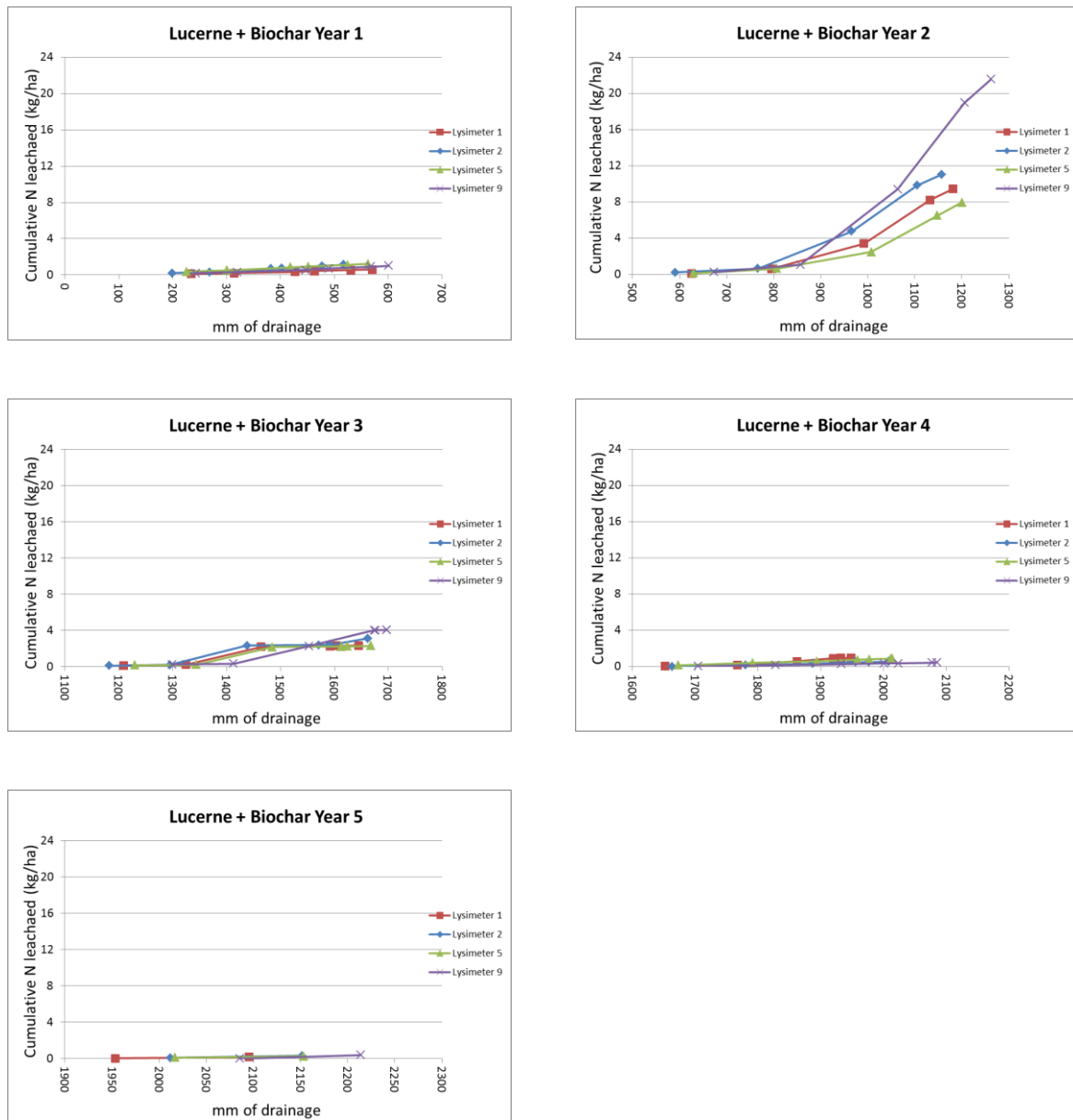


Figure 12 Drainage and cumulative N leached from four replicated lysimeters cultivated and sown in lucerne amended with biochar. Each ‘year’ represents a drainage period, and specific dates were as follows: Year 1 = 24/07/11–01/02/12; Year 2 = 25/05/12–17/11/12; Year 3 = 20/06/13–31/01/14; Year 4 = 28/06/14–29/12/14; Year 5 = 02/06/15–07/07/15.

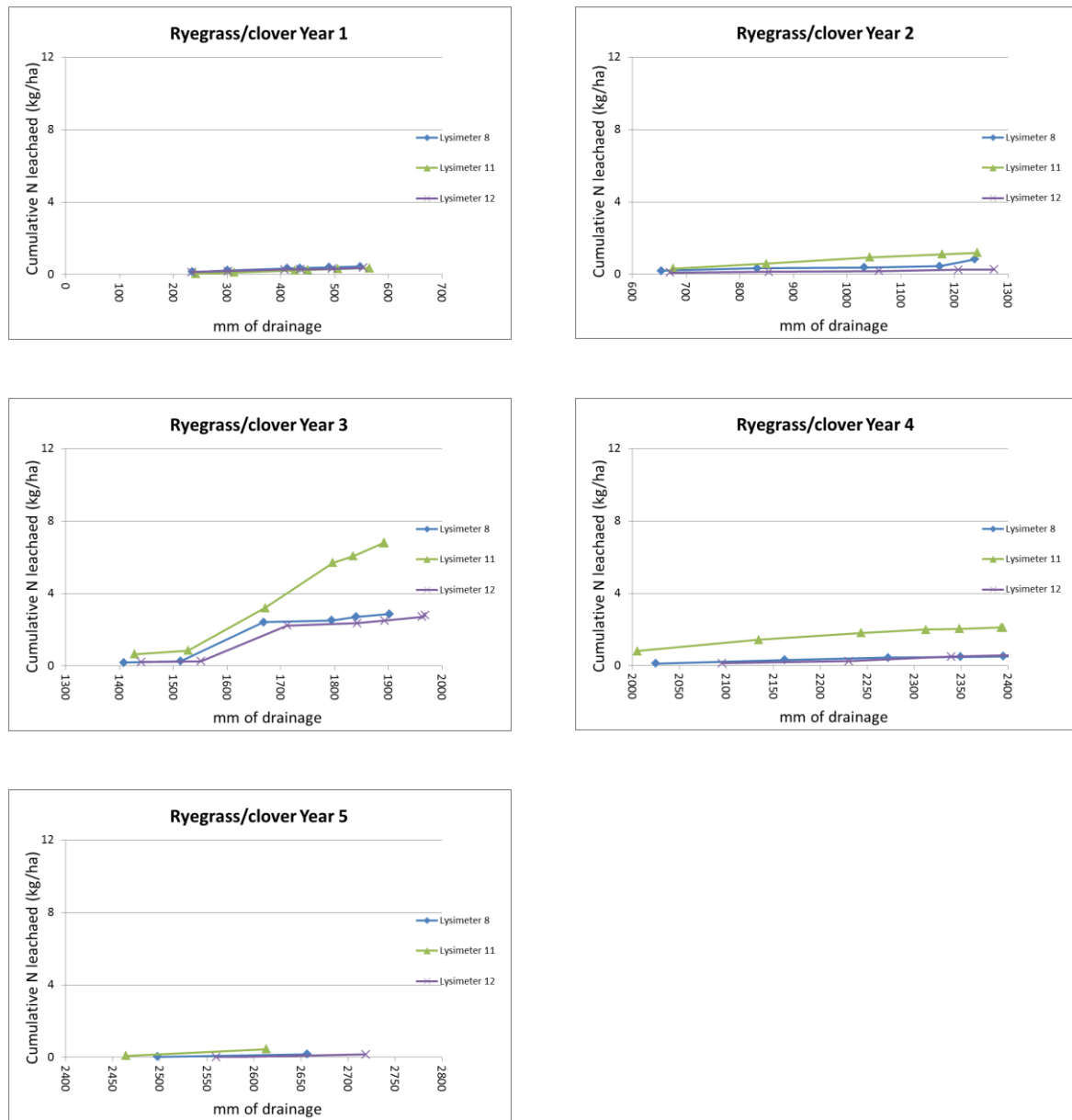


Figure 13 Drainage and cumulative N leached from four replicated lysimeters from established ryegrass/clover pasture. Each ‘year’ represents a drainage period, and specific dates were as follows: Year 1 = 24/07/11–01/02/12; Year 2 = 25/05/12–17/11/12; Year 3 = 20/06/13–31/01/14; Year 4 = 28/06/14–29/12/14; Year 5 = 02/06/15–07/07/15.

Appendix C – Average monthly air and soil temperatures, 2011-2014

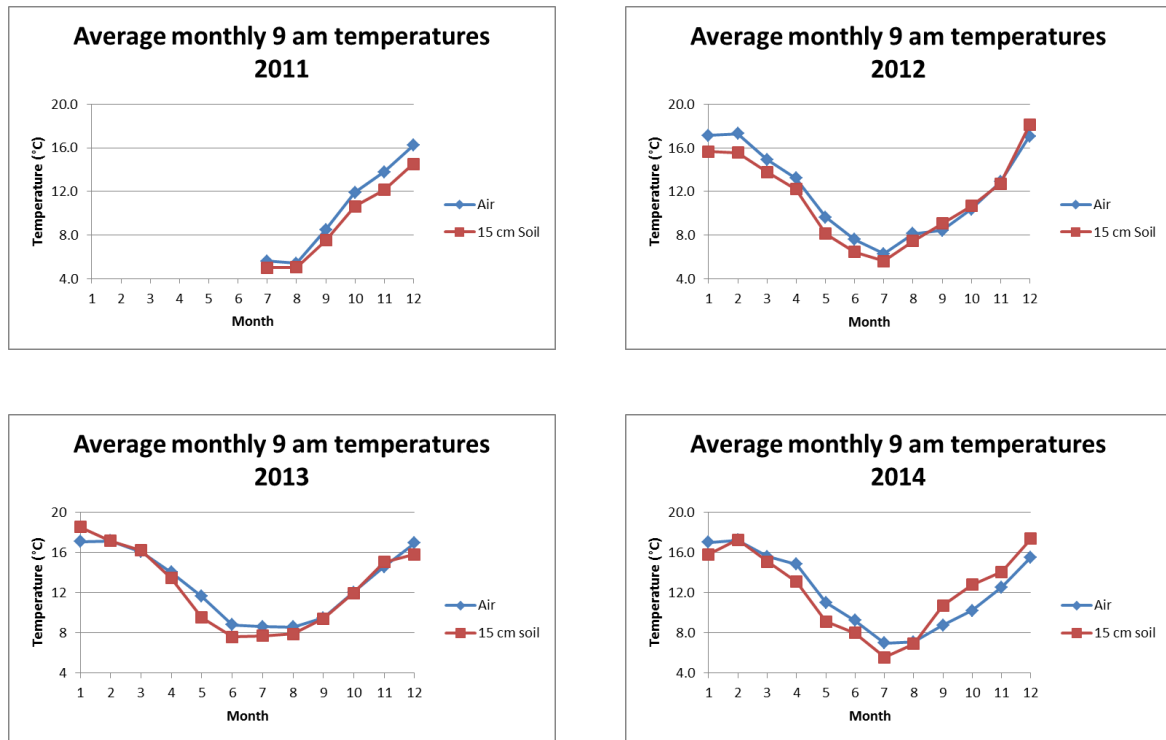


Figure 14 Average monthly 9am air temperatures and 15 cm soil temperatures for the 2011–2014 period at the lysimeter facility, Tihoi.

Appendix D – Average monthly rainfall, 2011-2014

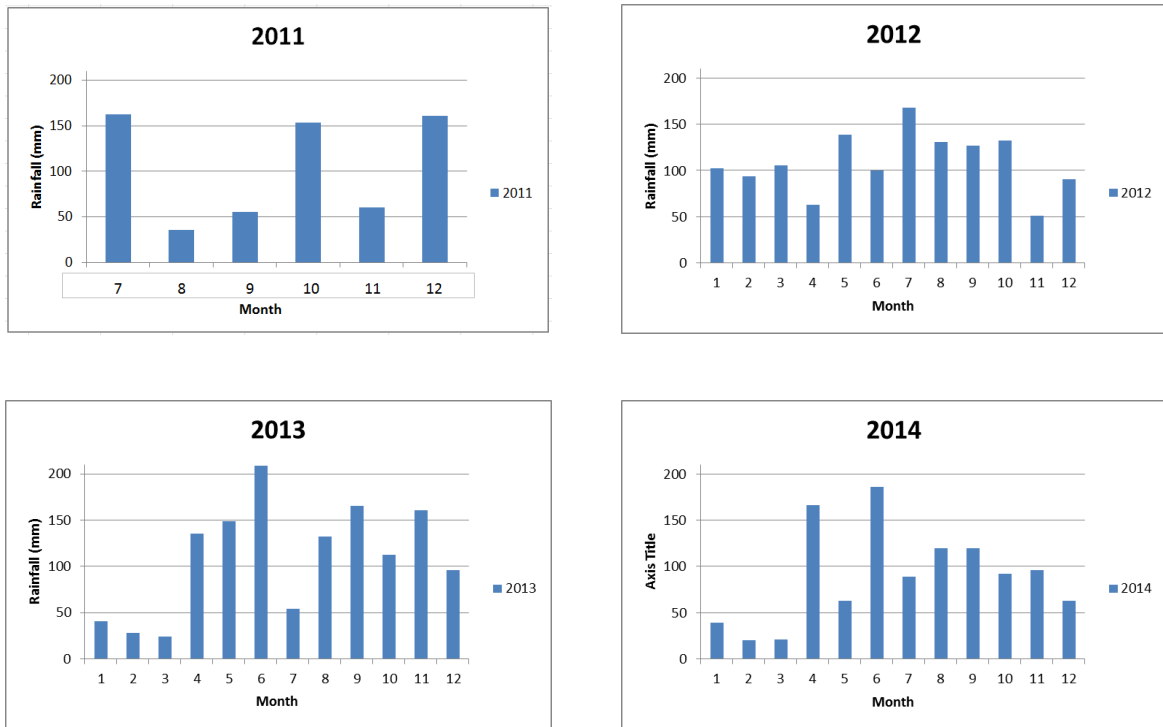


Figure 15 Average monthly rainfall for the 2011–2014 period at the lysimeter facility, Tihoi.

Appendix E – Soil analyses results

Table 4 Replicate physical analyses of the soil at the lysimeter site

Horizon depth (cm)	Sample depth (cm)	Dry bulk density (t/m ³)	Total porosity (%, v/v)	Vol. WC 5 kPa (%, v/v)	Vol. WC 10 kPa (%, v/v)	Vol. WC 20 kPa (%, v/v)	Vol. WC 40 kPa (%, v/v)	Vol. WC 100 kPa (%, v/v)	Vol. WC 1500 kPa (%, v/v)	Readily available water (%, v/v)	Total available water (%, v/v)
0 - 15	5.5 - 8.5	0.76	67.4	44.1	37.7	30.1	25.8	22.9	15.3	14.8	22.5
	5.5 - 8.5	0.76	67.6	45.8	38.6	30.7	26.0	22.9	18.7	15.7	20.0
15 - 30	21 - 24	0.69	70.8	37.4	29.3	21.0	17.0	14.9	9.5	14.4	19.8
	21 - 24	0.63	73.4	36.7	27.0	17.7	14.5	13.0	9.7	14.0	17.3
30 - 44	34 - 37	0.67	71.0	44.3	38.4	29.8	25.3	21.9	8.7	16.4	29.7
	34 - 37	0.74	68.2	43.1	36.9	28.5	24.3	20.7	9.3	16.1	27.6
44 - 66	53 - 56	0.82	65.3	49.0	41.0	29.6	23.6	17.8	6.6	23.2	34.4
	53 - 56	0.85	64.6	49.8	42.6	32.1	25.5	19.4	7.2	23.2	35.4
66 - 84	71 - 74	0.94	60.3	46.4	43.3	34.5	28.5	21.7	7.1	21.6	36.2
	71 - 74	0.94	60.2	46.1	41.5	32.4	26.2	19.8	7.1	21.7	34.4
84-150	115 - 118	0.57	77.1	59.3	55.1	51.9	50.4	47.5	34.3	7.6	20.7
	115 - 118	0.58	76.9	59.9	56.3	53.5	52.0	49.1	33.4	7.2	22.9