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Rootzone reality: technical review on network performance

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EXECUTIVE SUMMARY

Rootzone reality: technical review on network performance

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In July 2014 a network of passive-wick tension fluxmeters was established on 12 commercial cropping farms in the Canterbury, Manawatu, Hawke's Bay, Waikato and Auckland regions. The network is being used to quantify leaching losses of nitrogen (N) and phosphorus (P) in drainage water from below the crop rootzone. In this report we review the technical performance of the fluxmeter network for the period 1 October 2014 to 28 February 2018. This includes an evaluation of measured drainage volumes against modelled outputs (generated using a mechanistic soil water balance model) and a summary of N and P losses in drainage water from each site. At most sites, this reporting period represents at least 3 years of continuous data collection allowing for multiple crop rotations and the dissipation of settling effects following installation of the fluxmeter units.

From this review we conclude that eleven of the twelve fluxmeter sites are operating in a manner suitable for the generation of robust data on N and P losses in drainage water (Table i). Only at one site (Site 8) were serious concerns raised about the performance of some fluxmeters, a number of which captured no drainage in the 41 months of monitoring. At all other sites, the fluxmeter units were found to be operational and effective at capturing drainage, despite sometimes large variations in volumes captured by individual units. Drainage variability was attributed to different patterns of accumulation across the sites as affected by topography, soil physical properties and crop factors. At seven of the sites (Sites 1, 2, 3, 4, 5, 6 and 10), captured drainage volumes were highly consistent with the timing of drainage events and patterns of drainage accumulation as predicted by the soil water balance model (Table i). At the remaining five sites (excluding Site 8), and during certain periods, captured drainage volumes deviated from modelled predictions. This was attributed to flooding of the fluxmeters resulting in excess capture volumes (Sites 7, 11 and 12) or inefficient drainage collection resulting in reduced capture volumes (Site 9). Where flooding occurred, N and P losses were estimated using a combination of modelled drainage and measured concentration data, an approach that is common for other sampling methods such as suction cups. Concentration data from flooded units were carefully evaluated to ensure that values were representative of drainage permeating through the soil profile, as opposed to bypass flow or ground water infiltration. At Site 9, we are awaiting soil physical characterisation results to confirm whether captured volumes are indeed being underestimated.

Inorganic N losses have varied widely across the network sites ranging from 0.5 to 234 kg N/ha (Year 1; 1 September 2014 to 30 August 2015), 2 to 173 kg N/ha (Year 2; 1 September 2015 to 30 August 2016), 16 to 203 kg N/ha (Year 3; 1 September 2016 to 30 August 2017) and 3 to 118 kg N/ha (Year 4, part; 1 September 2017 to 28 February 2018) (Figure i). High net losses were associated with high drainage volumes and inorganic N concentrations (predominantly nitrate-N) in drainage water. In most cases drainage losses occurred during the late autumn, winter and/or early spring months when rainfall and soil moisture contents were highest. Cumulative P losses in the respective Year 1, Year 2, Year 3 and current Year 4 monitoring periods ranged from 0.02 to 1.99 kg P/ha, 0.05 to 0.28 kg P/ha, 0.04 to 0.67 kg P/ha and 0.01 to 0.10 kg P/ha (Figure i). These represented fairly small net losses, of which the majority (50–95%) was in the dissolved reactive form (DRP) in the drainage water.

Table i. Summary of performance for the 12 fluxmeter sites for the period 1 September 2014 to 28 February 2018.

Site	Site Performance [1]	Description
1	✓	Site performing well
2	✓	Site performing well
3	✓	Site performing well
4	✓	Site performing well
5	✓	Site performing well
6	✓	Site performing well
7	✓?	Interpret with some caution: Modelled drainage and measured concentrations used to estimate losses in Years 3 and 4
8	×	Poor data and concerns about performance of fluxmeters
9	✓?	Interpret with some caution: drainage potentially underestimated
10	✓	Site performing well
11	✓?	Interpret with some caution: Modelled drainage and measured concentrations used to estimate losses in Years 1, 2 and 3
12	✓?	Interpret with some caution: Modelled drainage and measured concentrations used to estimate losses in Year 4

[1] ✓ = Performing well with no serious concerns. ✓? = Some concerns related to high or low drainage volumes, however, fluxmeters are effectively capturing drainage. × = Poor data; fluxmeters not operating effectively.

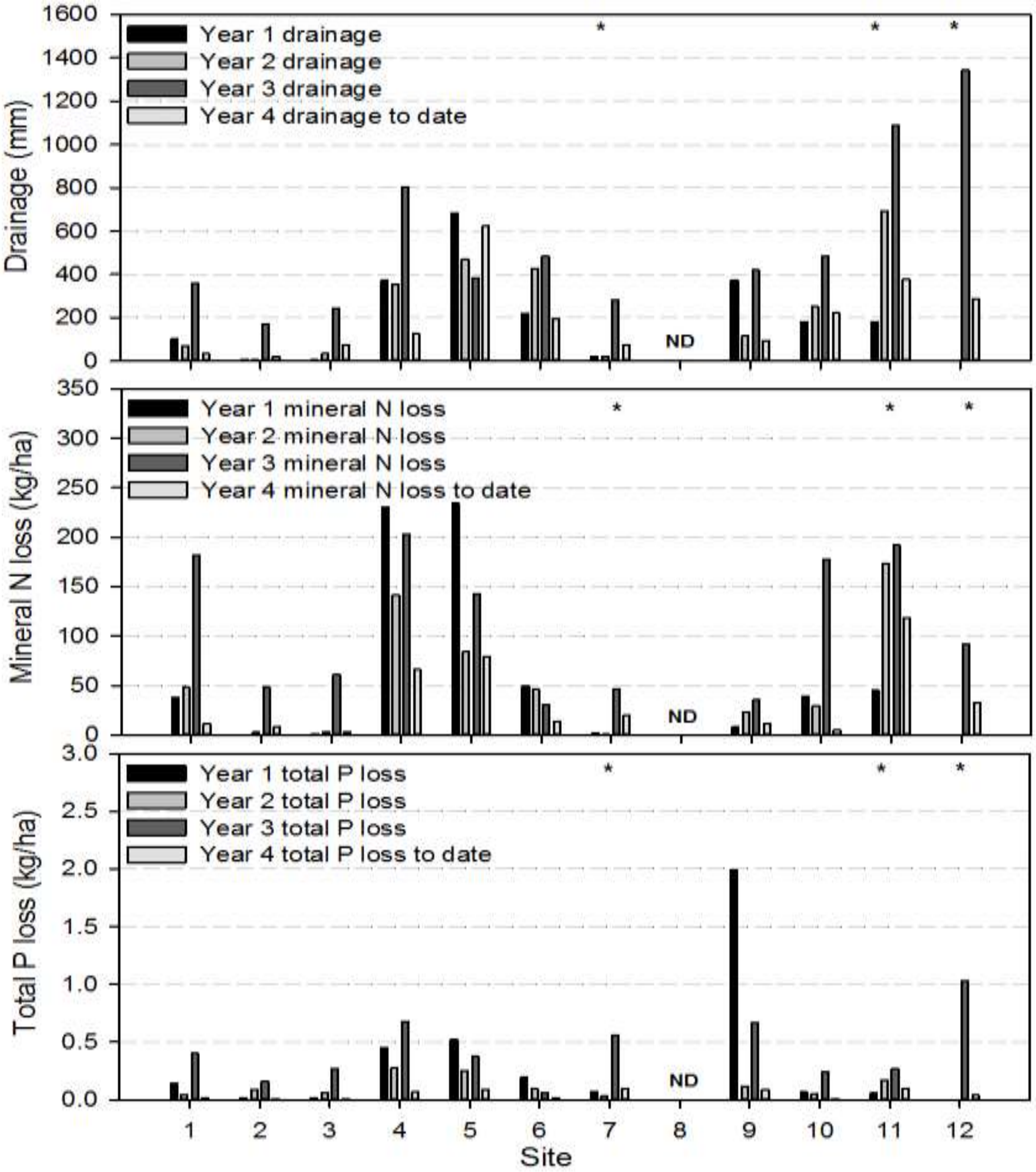

Figure i. Summary of annual drainage volumes and mineral nitrogen (N) and total phosphorus (P) annual losses in drainage across the 12 fluxmeter sites for the Year 1 (1 September 2014 to 30 August 2015), Year 2 (1 September 2015 to 30 August 2016), Year 3 (1 September 2016 to 30 August 2017) and current Year 4 (1 September 2017 to 28 February 2018) monitoring periods. Losses at Site 7 (Years 3 and 4), Site 11 (Years 1, 2 and 3) and Site 12 (Year 3) have been calculated using modelled drainage volumes and measured nutrient concentrations (*). No data (ND) is presented for Site 8 due to concerns about data integrity. At Site 12, data reflects the monitoring period between 15 June 2016 (site reinstallation) and 28 February 2018.

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1 INTRODUCTION

Between August 2014 and May 2015, a network of tension fluxmeters was installed on commercial cropping farms around New Zealand to measure losses of nitrogen (N) and phosphorus (P) in drainage water. The project was funded by the Ministry for Primary Industries (Sustainable Farming Fund), the Foundation for Arable Research, Horticulture NZ, Environment Canterbury, Horizons Regional Council, Hawke's Bay Regional Council, Waikato Regional Council, Auckland Council and Ravensdown. Twelve sites were established across five regions (Canterbury, Manawatu, Hawke's Bay, Waikato and Auckland) with results used to inform good management practices (GMP) for improved nutrient use efficiency. Data from the project have also be made available for future efforts to improve predictive models that can either be used to manage crops or inform policy development.

A key question regarding the network has been the functional performance of the fluxmeter units which are being used to capture drainage in situ from below the crop rootzone. Fluxmeters were selected as the preferred means of quantifying losses for a number of reasons including ease of management, cost effectiveness and their ability to capture entire drainage events. Nevertheless, as with other methods for quantifying leaching losses (e.g. suction cups and lysimeters), draw backs exist including the management of spatial variability (related to the narrow convergence zone), installation processes which disturb the soil profile and specific technical limitations. These include high water tables which can flood units and stony soil profiles which make installation difficult. In this regard, validation of the long term drainage volumes captured by the fluxmeter units is crucial and forms the basis for confidence in both current and future data sets.

In this report, after more than 3 years' operation, we provide a technical review on the performance of the fluxmeter network for the period 1 October 2014 to 28 February 2018. Such an evaluation we consider is best carried out after the fluxmeters have had time to 'settle in', and been exposed to a variety of weather conditions. Our assessment includes an evaluation of measured drainage volumes against modelled outputs generated with a mechanistic soil water balance model, plus a summary of N and P losses in drainage from the 12 sites. At most sites this reporting period represents at least 3 years of continuous data collection, allowing for multiple crop rotations and the dissipation of settling effects following installation of the fluxmeter units.

2 METHODS AND MATERIALS

A full description of the trial design, fluxmeter installation processes and measurements is provided in Norris et al. 2017. A brief overview is provided here for context.

2.1 Experimental design

The basic experimental design across the fluxmeter network included five monitor regions (Canterbury, Manawatu, Hawke's Bay, Waikato and Auckland), three sites per region and 12 fluxmeters per site. The tops of the fluxmeters were installed to a depth of 1 m and all sites are located on commercial properties covering a range of cropping systems, soil types, climatic conditions and management practices relevant to each region (Figure 1a). At each site, the layout of fluxmeters was in three clusters of four units spaced 4 m apart around a central collection sump. The approximate distance between sumps was 25 to 40 m. Twelve fluxmeters were installed at each site to account for spatial variability.

Fluxmeters were made from cylindrical PVC piping, 120 cm long with a 20 cm wide convergence zone for drainage interception (Figure 1b). In the convergence zone fine silica sand was packed on top of diatomaceous earth to filter drainage water before it entered the storage tank. A passive wick, the top of which was unthreaded and mixed into the diatomaceous, ensured that water only entered the storage tank when soil moisture was at or above the pressure head imposed by the 600 mm length of the hanging wick, preventing preferential flow into the tank. The maximum storage volume in each tank was 14 L. Attached to each fluxmeter were two small-gauge plastic tubes to remove drainage water under suction during sampling events. Once installed, the units are designed to remain in the soil for an extended period. A summary of the design and functionality of fluxmeter units is provided by Gee et al. (2009) and Meissner et al. (2010).

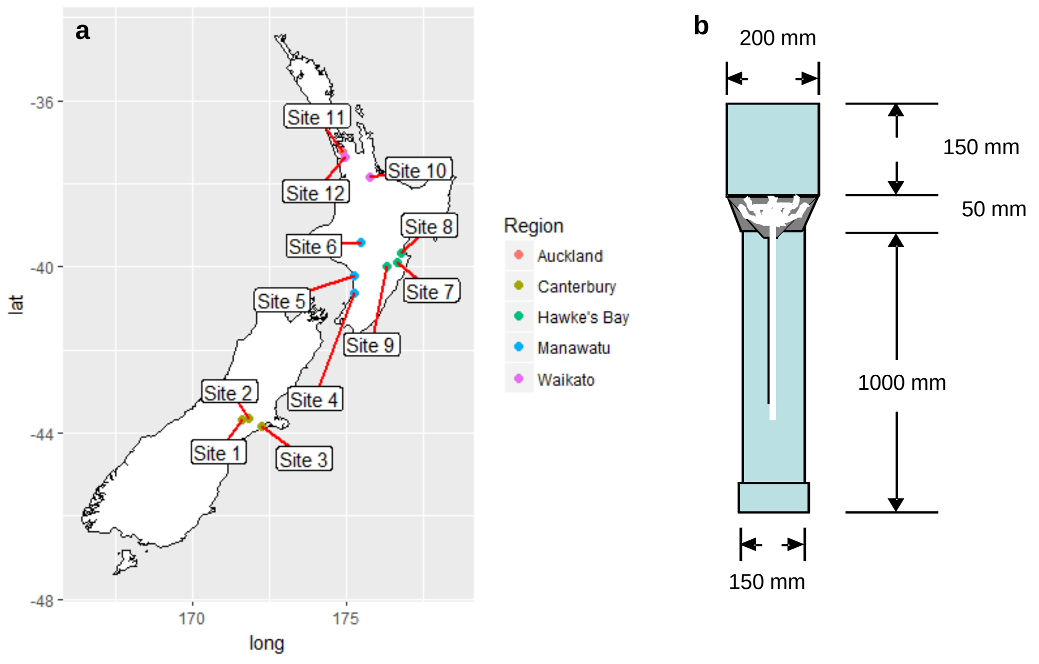

Figure 1. Location of the 12 fluxmeter sites (a) and design of the passive wick tension fluxmeter (b).

2.2 Measurements and analysis

A range of soil, plant and drainage measurements were collected from the network sites. For the purposes of this technical report, we focus on drainage and soil physical measurements.

Drainage samples were routinely collected from the fluxmeter units with collection frequency dependent on a range of site specific factors including management practice (e.g. irrigation), climate (e.g. rainfall) and soil physical properties that influence drainage. On each sampling occasion, drainage was removed from the buried fluxmeters with an electric suction pump. The maximum number of samples on any sampling occasion was 12; one inorganic N and dissolved reactive phosphorus (DRP), one for total P and one spare. Following collection, drainage volumes were recorded and three 40 mL samples retained from each fluxmeter for further analyses (one inorganic N and DRP, one for total P and one spare). Samples for inorganic N and DRP analysis were pre-filtered in the field using Axiva™ syringe filters (0.45 micron). The remaining samples were not filtered. Following collection the samples were frozen until further analysis by an International Accreditation New Zealand (IANZ) accredited laboratory.

Soil samples for physical and hydraulic characterisation were taken from all of the sites with results used to parameterise the soil water balance model (see Section 2.4). At the time of this report, results were available for Sites 3, 5, 6, 8, 10, 11 and 12 and pending for Sites 1, 2, 4, 7 and 9 (analysis takes 2–3 months). Sampling involved excavating a 1.2 m deep pit and taking intact cores from the 0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm and 80–100 cm depths. The specific core depth within each sampling layer was adjusted to avoid soil horizon interfaces. Three sampling pits were excavated giving a total of 15 samples, or three replicates per depth layer. Samples were analysed at a soil physics laboratory for a range of physical and hydraulic measures including gravimetric and volumetric water contents at 0, -5, -10 (field capacity), -100 and -1500 (permanent wilting point) kPa.

2.3 Supplementary data

Weather data for each site (daily and long-term) were collated from a range of sources including the National Institute of Water and Atmospheric Research’s (NIWA) climate database, regional council weather stations and onsite loggers. For each site, a combination of sources were used to provide data which were both the most representative. Observations included daily air temperature (minimum, mean and maximum), solar radiation, rainfall, vapour pressure, wind run and mean sea level pressure (MSLP). Climate data sources for each site are presented in Appendix 1.

2.4 Modelling drainage

A soil water balance was generated at each site using a variation of The New Zealand Institute for Plant and Food Research Limited’s mechanistic Soil-Plant-Atmospheric-Model (SPASMO) (Green 2011; Green et al. 2012). The model considers water movement through a one-dimensional soil profile that extends from the soil surface to a depth of 120 cm with the water balance calculated as a function of inputs (rainfall and irrigation) and losses (transpiration, evaporation, run-off and drainage) of water from the soil profile. The seasonal pattern of crop development is expressed using the dual crop-factor approach, following FAO-56 guidelines for computing crop water requirements (Allen et al. 2005). Each crop has a specified root depth and drought tolerance. The model assumes that crop management factors are optimised to mitigate plant stress. Soil physical and hydraulic properties (bulk density, stone content and soil water holding characteristics) were defined using data from onsite soil physical characteristics sampling (Sites 3, 5, 6, 8, 10, 11 and 12) or from data derived from the New Zealand Soils database (Sites 1, 2, 4, 7 and 9). Soil water retention curves (0–30 cm, 30–60 cm, 60–90 cm and 90–120 cm depths) were generated using the Van-Genuchten (1980) equation with fitting parameters for the curves determined with Microsoft® Excel's® non-linear routine SOLVER function. Surface run-off was based on daily rainfall totals using the Soil Conservation Service (SCS) curve number approach (Williams 1991).

2.5 Data analysis

The R software package (R Core Team 2017) was used to summarise drainage and nutrient loss data including calculation of means, standard errors (SE) and coefficients of variation (CV). Also R was used for graphical presentation. Drainage for each collection event was calculated by taking the mean sample volume across all fluxmeters, including units with zero drainage, but excluding units where volumes were deemed to be outside a threshold for acceptance. Excluded values, termed outliers, were defined as being 1.5 times greater than the rainfall volume for the collection period in question. This process allowed for obvious outliers to be identified, for example where units were flooded, while allowing for the inclusion of some drainage volumes which, while considerably different modelled predictions, were still considered to be believable. Data were also excluded from analysis when concentration values were deemed to be erroneous (e.g. sample contamination with sediment),or where a fluxmeter was faulty. N and P flux (kg/ha) for individual fluxmeters was calculated as a function of capture area, drainage volume and nutrient concentration in the drainage water. Outliers were excluded in the calculation of mean losses for each collection period.

3 RESULTS

In this section we assess the performance of each of the fluxmeter sites by evaluating captured drainage volumes against the SPASMO-modelled outputs. Data are presented for the period 1 September 2014 and 28 February 2018, which at most sites covers a period of three and a half years. The N and P losses have been reported on a yearly basis covering the Year 1 (1 September 2014 to 30 August 2015), Year 2 (1 September 2015 to 30 August 2016), Year 3 (1 September 2016 to 30 August 2017) and the current Year 4 (1 September 2017 to 28 February 2018) reporting periods. Supplementary data relating to climate data collection sources, total drainage volumes for each fluxmeter unit and N and P concentrations in drainage water are provided in Appendices 1, 2, 3 and 4 respectively.

3.1 Site 1

3.1.1 Site overview

Site 1 is located near Methven on a mixed cropping and livestock grazing enterprise. The soil type is a Mayfield silt loam (*typic argillic pallic*). Since installation of the fluxmeters in August 2014 there have been five crop sequences including ryegrass seed, ryegrass pasture, spring wheat, barley and plantain (the current crop) (see Figure 3a).

3.1.2 Site performance

Data from the past three and a half years indicate that the site is performing well. Average measured drainage for the monitoring period (41 months) has totalled 564 mm, comparable to the 586 mm predicted by the soil water balance model (Figure 2a). During this time all 12 fluxmeters were effective at capturing drainage with cumulative totals (excluding outliers) ranging from 131 to 1483 mm (median = 401 mm, CV = 76%; Appendix 2). The wide range in cumulative totals reflect different patterns of drainage accumulation across the site as affected by topography, soil physical and crop factors. There were 30 sampling events (in three of these no drainage was recorded) and the average number of samples used to calculate mean drainage volumes and nutrient losses was 11.9 (range was 11 to 12).

A similar pattern of drainage accumulation was observed for modelled and measured data with modest accumulation observed until June 2016 (< 200 mm) followed by increased accumulation in the second half of the monitoring period (July 2016 to February 2018). Most drainage occurred between January and October 2017 with 302 mm recorded during this period (54% of the total).

Drainage events occurred as predicted by the model except for a period between February and August 2016 when several small events (1.8 to 13.8 mm) were captured by the fluxmeters in contrast to the model which predicted none. Rainfall and irrigation data were collated from offsite sources (Appendix 1) until April 2017 and during periods where logging equipment was removed to allow for management activity. Consequently, modelled versus measured discrepancies may relate to these non-site specific data. Samples for soil physical and hydraulic characterisation were taken in April 2018 and results from these analysis will be incorporated into the model as they become available. The soil water retention curves used to parameterise the model are presented in Appendix 5a.

3.1.3 Nitrogen and phosphorus losses in drainage

Inorganic N losses were 288 kg/ha for the period 1 September 2014 to 28 February 2018 with respective Year 1, Year 2, Year 3 and current Year 4 period losses totalling 38, 48, 182 and 11 kg N/ha (Figure 3b). Nitrate-N was the predominant form of inorganic N in captured drainage with concentrations averaging 50.6 mg/L over the monitoring period (range in mean concentrations was 5.9–91.7 mg/L). Very high inorganic N losses were observed in Year 3 (182 kg/ha) reflecting both high nitrate-N concentrations in drainage samples (average for this period was 68.5 mg/L) and increased drainage volumes (average for this period was 359 mm) compared to previous years (85 and 98 mm for respective Year 1 and Year 2 periods). A histogram of nitrate-N concentrations in drainage is provided in Appendix 3a.

Total P losses were 0.61 kg/ha for the period 1 September 2014 to 28 February 2018 with respective Year 1, Year 2, Year 3 and current Year 4 period losses totalling 0.14, 0.05, 0.40 and 0.02 kg P/ha (Figure 3c). These losses are low, reflecting primarily low concentrations of total P in drainage water. Excluding the first collection event in November 2014 where some sediment was present in samples following installation, the respective total P and DRP concentrations averaged 0.10 and 0.07 mg/L for the three and a half year monitoring period. A histogram of total P concentrations in drainage is provided in Appendix 4a.

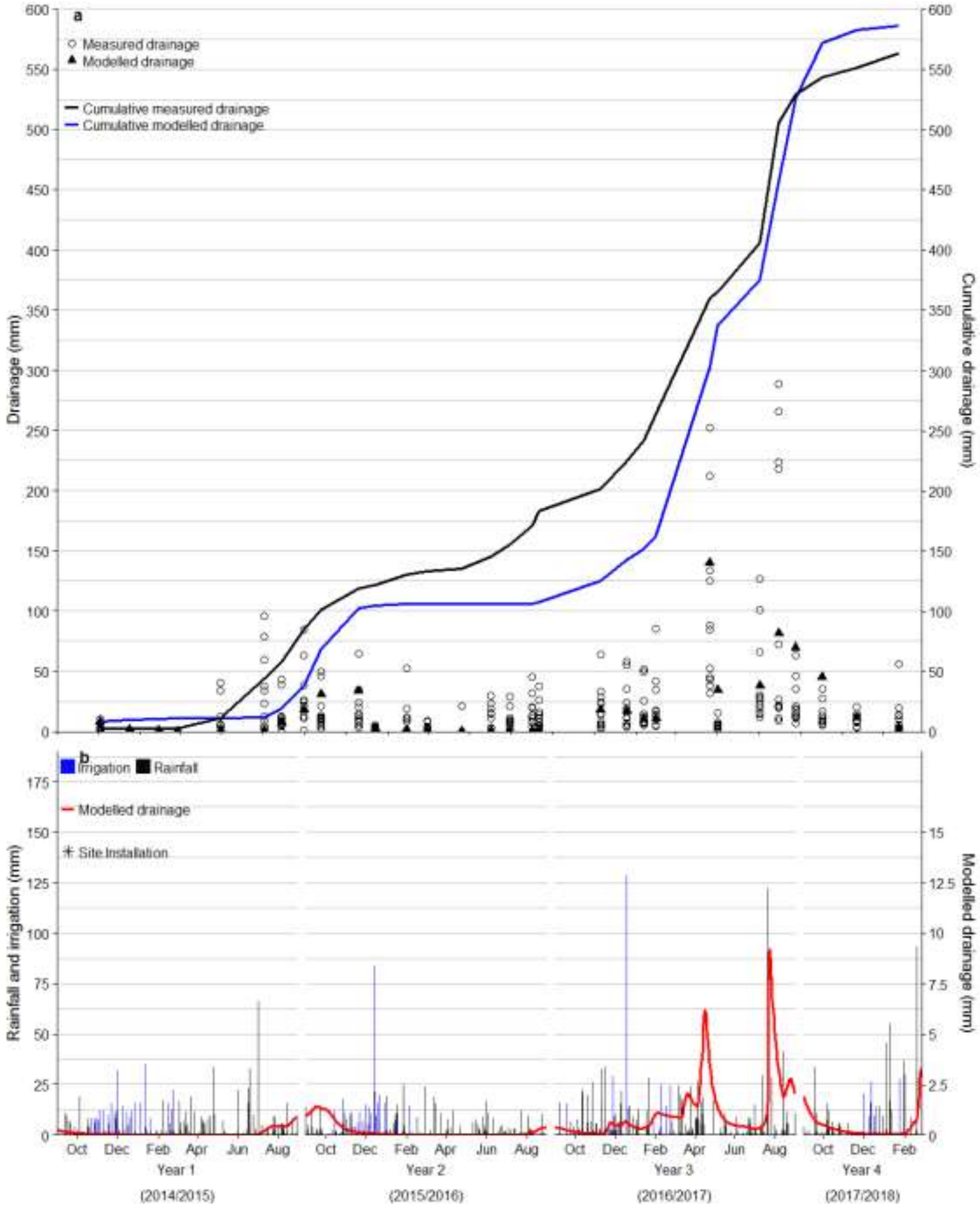

Figure 2. Comparison of measured and modelled drainage data (including drainage volumes for each of the 12 individual fluxmeter units) (a) in conjunction with rainfall and irrigation inputs and modelled drainage at 100 cm (b) at Site 1, Canterbury for the Year 1 (1 September 2014 to 30 August 2015), Year 2 (1 September 2015 to 30 August 2016), Year 3 (1 September 2016 to 30 August 2017) and current Year 4 (1 September 2017 to 28 February 2018) reporting periods. Modelled data was generated using the mechanistic Soil-Plant-Atmospheric-Model (SPASMO). The site was installed on 26 August 2014.

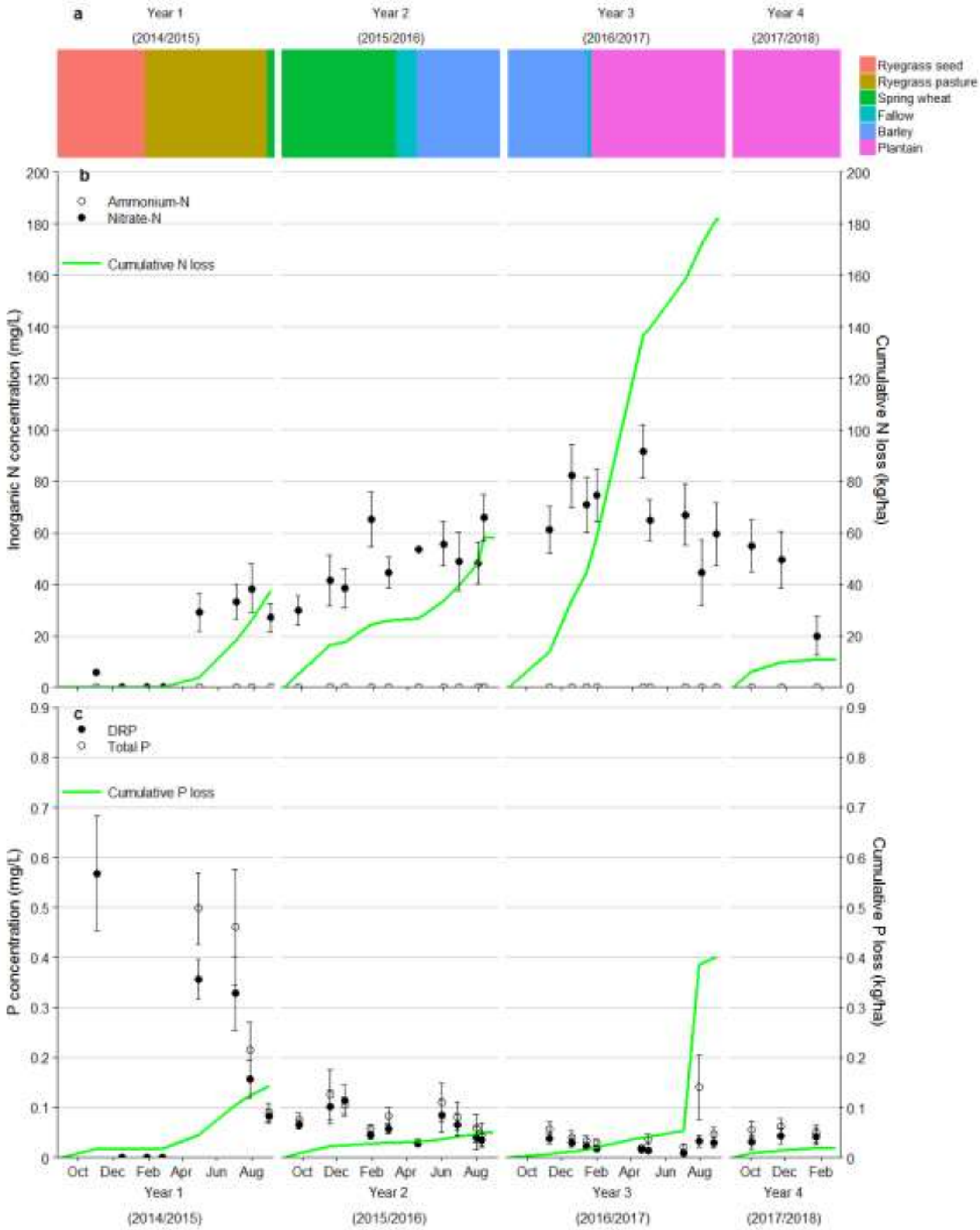

Figure 3. Sequence of crops (a), nitrate and ammonium concentrations and cumulative inorganic nitrogen (N) loss in drainage (b) and total phosphorus (P) and dissolved reactive phosphorus (DRP) concentrations and cumulative total P loss in drainage (c) at Site 1, Canterbury for the Year 1 (1 September 2014 to 30 August 2015), Year 2 (1 September 2015 to 30 August 2016), Year 3 (1 September 2016 to 30 August 2017) and current Year 4 (1 September 2017 to 28 February 2018) reporting periods. Bars around each point represent the standard error of the mean.

3.2 Site 2

3.2.1 Site overview

Site 2 is located near Methven on a mixed cropping and livestock grazing enterprise. The soil type is a Barrhill silt loam (*typic immature pallic*). Since installation of the fluxmeters in September 2014 there have been five crop sequences including barley, white clover seed, white clover grazing, carrots and wheat. The site is currently fallow (see Figure 5a).

3.2.2 Site performance

The site is performing satisfactorily. Average measured drainage for the monitoring period (41 months) totalled 205 mm, 35% less than the 313 mm predicted by the soil water balance model (Figure 4a). Despite this discrepancy, the general pattern of drainage accumulation was similar for modelled and measured data with minimal drainage recorded up to December 2016 (15 mm) followed by several notable events between May and September 2017. Most drainage (82%) was recorded during this latter period. The largest differences between modelled and measured values occurred between December 2016 and August 2017 when 162 mm was predicted by the model compared to 65 mm collected in the fluxmeters. Rainfall and irrigation data were collated from offsite sources until April 2017 (Appendix 1) and during periods where logging equipment was removed to allow for management activity. Consequently, modelled versus measured discrepancies may relate to the use of these non-site specific data in the modelling. Samples for soil physical and hydraulic characterisation were taken in February 2018 and results from these analysis will be incorporated into the model as they become available. This may further reduce the variations between modelled and measured. The soil water retention curves used to parameterise the model are presented in Appendix 5a.

All 12 fluxmeters were effective at capturing drainage over the monitoring period with cumulative drainage totals ranging from 114 to 500 mm (median = 140 mm; CV = 66%; Appendix 2). The wide range in cumulative totals reflect different patterns of drainage accumulation across the site as affected by topography, soil physical and crop factors. There were 27 sampling events (in 15 of these no drainage was recorded) and the average number of samples used to calculate mean drainage volumes and nutrient losses was 11.9 (range was 11 to 12).

3.2.3 Nitrogen and phosphorus losses in drainage

Inorganic N losses were 59 kg/ha for the period 1 September 2014 to 28 February 2018 with respective Year 1, Year 2, Year 3 and current Year 4 period losses totalling 0.5, 3, 48 and 8 kg N/ha (Figure 5b). The low losses observed in Years 1 and 2 reflected low drainage volumes. Similarly, increased losses in Year 3 reflected higher drainage volumes although nitrate concentrations were also increased for this period (average nitrate-N concentrations for respective Year 1, 2 and 3 period were 20.3, 16.2 and 30.1 mg/L). A histogram of nitrate-N concentrations in drainage is provided in Appendix 3a.

Total P losses were 0.27 kg/ha for the period 1 September 2014 to 28 February 2018 with respective Year 1, Year 2, Year 3 and current Year 4 period losses totalling 0.02, 0.09, 0.16 and 0.01 kg P/ha (Figure 5c). These losses are low, reflecting primarily low concentrations of total P in drainage water. The lack of drainage in Year 1 to assist with 'settling' of the units meant that total P and DRP concentrations remained comparatively high until September 2015. Thereafter, concentrations decreased considerably averaging 0.15 mg/L and 0.11 mg/L respectively for the Year 2, 3 and current Year 4 periods. A histogram of total P concentrations in drainage is provided in Appendix 4a.

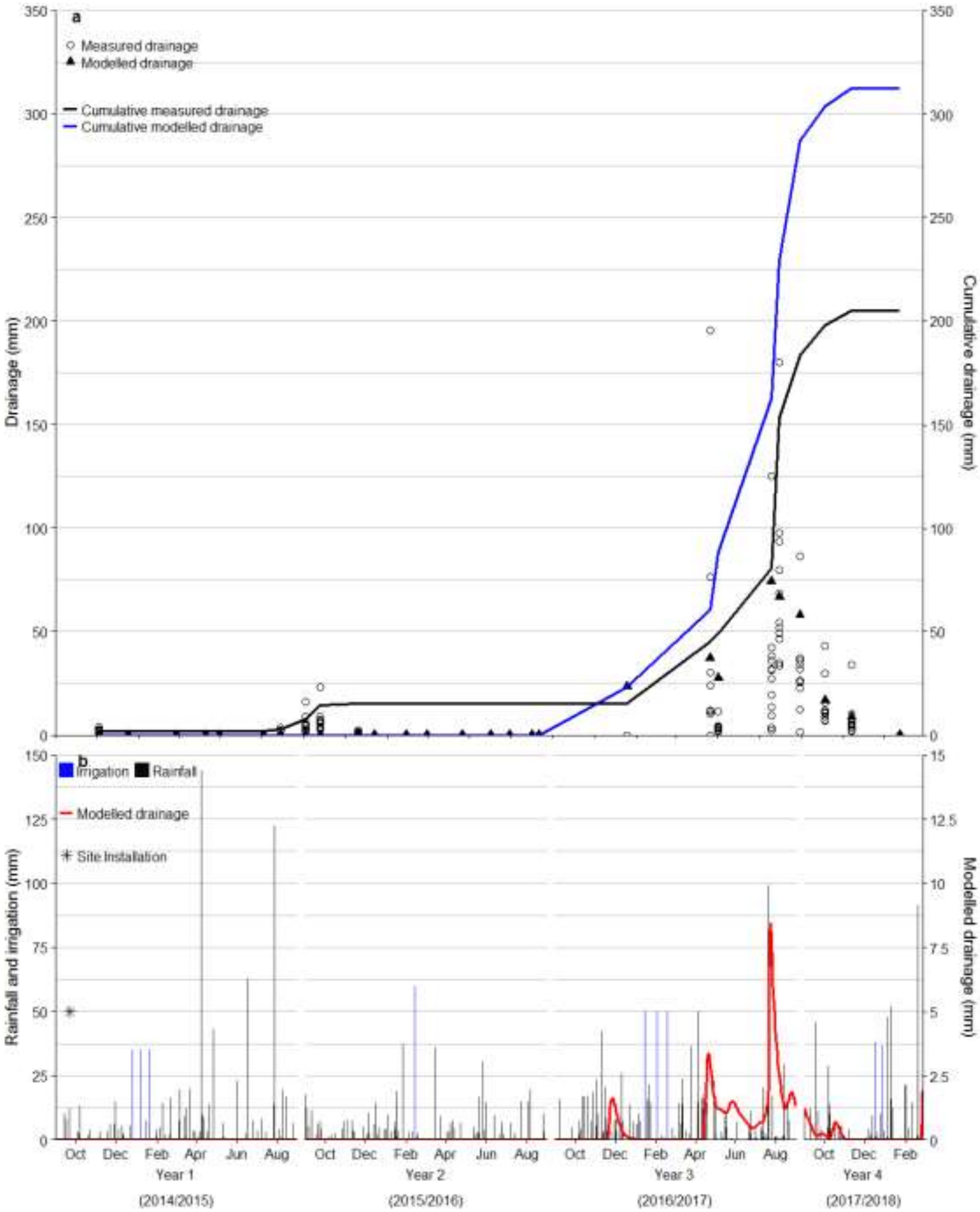

Figure 4. Comparison of measured and modelled drainage data (including drainage volumes for each of the 12 individual fluxmeter units) (a) in conjunction with rainfall and irrigation inputs and modelled drainage at 100 cm (b) at Site 2, Canterbury for the Year 1 (1 September 2014 to 30 August 2015), Year 2 (1 September 2015 to 30 August 2016), Year 3 (1 September 2016 to 30 August 2017) and current Year 4 (1 September 2017 to 28 February 2018) reporting periods. Modelled data were generated using the mechanistic Soil-Plant-Atmospheric-Model (SPASMO).

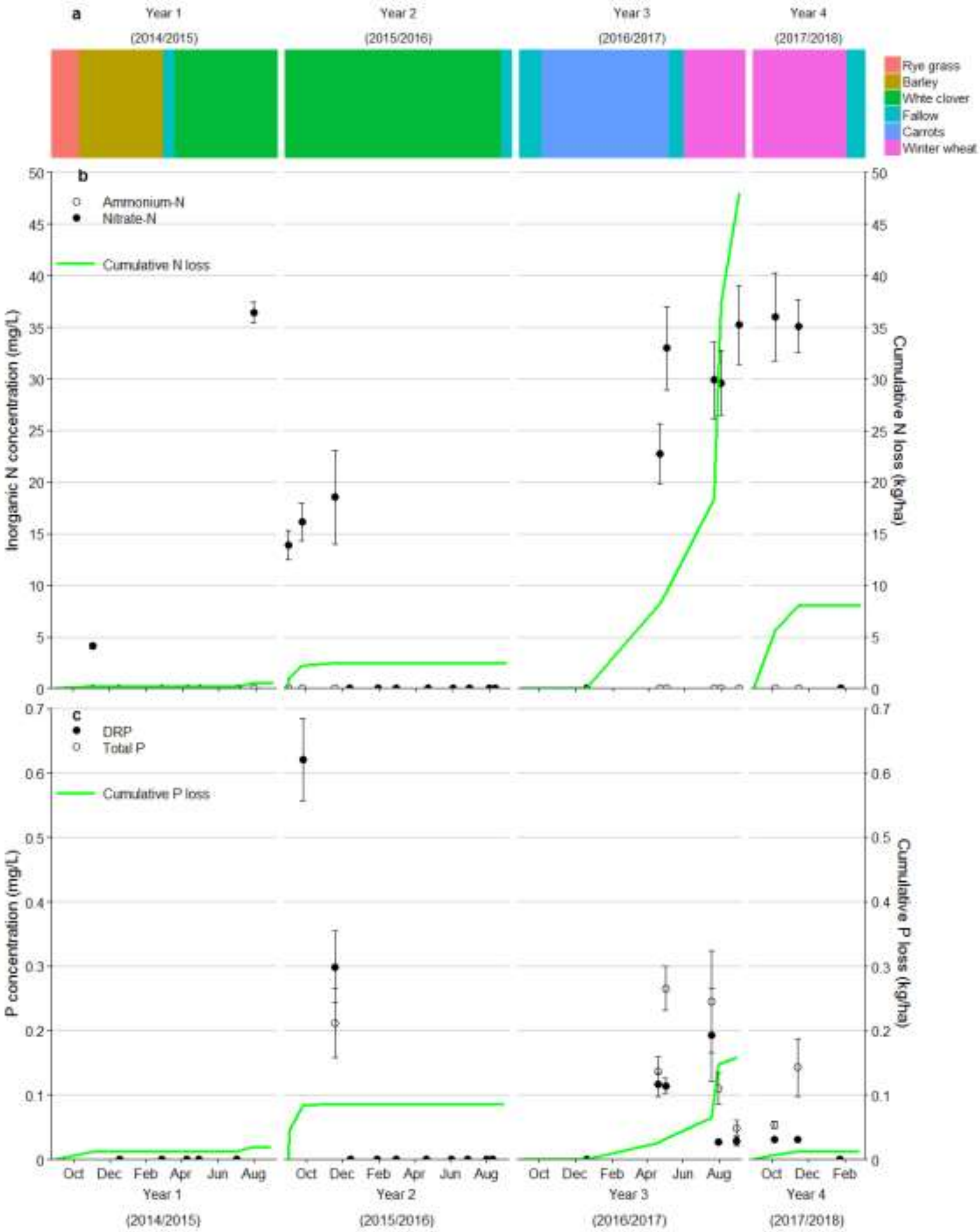

Figure 5. Sequence of crops (a), nitrate and ammonium concentrations and cumulative inorganic nitrogen (N) loss in drainage (b) and total phosphorus (P) and dissolved reactive phosphorus (DRP) concentrations and cumulative total P loss in drainage (c) at Site 2, Canterbury for the Year 1 (1 September 2014 to 30 August 2015), Year 2 (1 September 2015 to 30 August 2016), Year 3 (1 September 2016 to 30 August 2017) and current Year 4 (1 September 2017 to 28 February 2018) reporting periods. Bars around each point represent the standard error of the mean.

3.3 Site 3

3.3.1 Site overview

Site 3 is located near Southbridge on a mixed cropping and livestock grazing enterprise. The soil type is a Templeton loam (*typic immature pallic*). Since installation of the fluxmeters in September 2014 there have been five crop sequences including ryegrass seed, ryegrass pasture, process beans, forage oats and kale. The site is currently fallow (see Figure 7a).

3.3.2 Site performance

Data from the past three and a half years indicates that the site is performing well. Average measured drainage for the monitoring period (41 months) has totalled 294 mm, comparable to the 280 mm predicted by the soil water balance model (Figure 6a). During this time, all 12 fluxmeters were effective at capturing drainage with cumulative totals ranging from 63 to 587 mm (median = 285 mm; CV = 46%; Appendix 2). The wide range in cumulative totals reflects different patterns of drainage accumulation across the site as affected by topography, soil physical and crop factors. There were 27 samplings (in 14 of these no drainage was recorded) and the average number of samples used to calculate mean drainage volumes and nutrient losses was 11.8 (range was 8 to 12).

There were a few small discrepancies between modelled and measured values, particularly in the Year 1 and initial Year 2 periods when four drainage events (1 to 6 mm) were recorded in contrast to zero predicted by the model. On the whole, however, a similar pattern of drainage accumulation was observed between measured and modelled data with low levels of drainage observed until May 2017 followed by increased accumulation from July 2017. Most drainage occurred between July and November 2017 with 254 mm recorded during this period (86% of the total; modelled sum was 222 mm). Rainfall and irrigation data were collated from offsite sources (Appendix 1) until April 2016 and during periods where logging equipment was removed to allow for management activity. Soil samples for physical and hydraulic characterisation were taken in April 2017 and results from these analyses were used to parameterise the soil water balance model (Appendix 5a).

3.3.3 Nitrogen and phosphorus losses in drainage

Inorganic N losses were 68 kg/ha for the period 1 September 2014 to 28 February 2018 with respective Year 1, Year 2, Year 3 and current Year 4 period losses totalling 1, 3, 61 and 3 kg N/ha (Figure 7 b). Nitrate-N was the predominant form of inorganic N in captured drainage with concentrations averaging 15.3 mg/L over the monitoring period (range in mean concentrations was 4.2 – 27.0 mg/L). Most of the losses in this period (90%) occurred during a single event in August 2017 when a large amount of drainage was recorded and average nitrate-N concentrations (24.1 mg/L) were increased compared to previous events (Figure 5b). Low losses for all other events reflected a combination of low drainage volumes and relatively low concentrations of nitrate-N in drainage water. A histogram of nitrate-N concentrations in drainage is provided in Appendix 3a.

Total P losses were 0.36 kg/ha for the period 1 September 2014 to 28 February 2018 with respective Year 1, Year 2, Year 3 and current Year 4 period losses totalling 0.02, 0.06, 0.27 and 0.01 kg P/ha (Figure 7c). These losses are low, reflecting primarily low concentrations of total P in drainage water. Excluding the first collection event in November 2014 where some sediment was present in samples following installation, respective total P and DRP concentrations averaged 0.27 and 0.20 mg/L for the three and a half year monitoring period. A histogram of total P concentrations in drainage is provided in Appendix 4a.

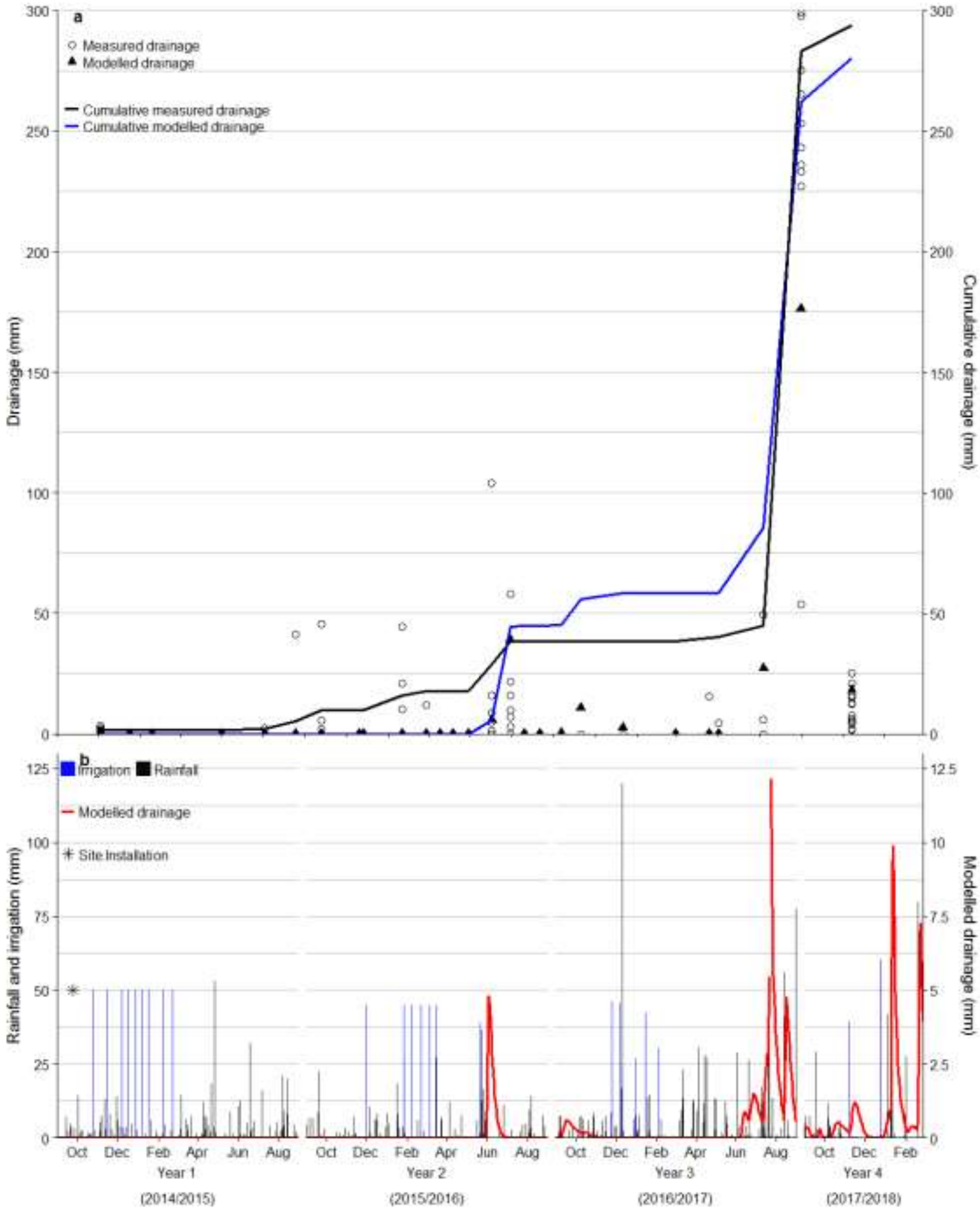

Figure 6. Comparison of measured and modelled drainage data (including drainage volumes for each of the 12 individual fluxmeter units) (a) in conjunction with rainfall and irrigation inputs and modelled drainage at 100 cm (b) at Site 3, Canterbury for the Year 1 (1 September 2014 to 30 August 2015), Year 2 (1 September 2015 to 30 August 2016), Year 3 (1 September 2016 to 30 August 2017) and current Year 4 (1 September 2017 to 28 February 2018) reporting periods. Modelled data were generated using the mechanistic Soil-Plant-Atmospheric-Model (SPASMO).

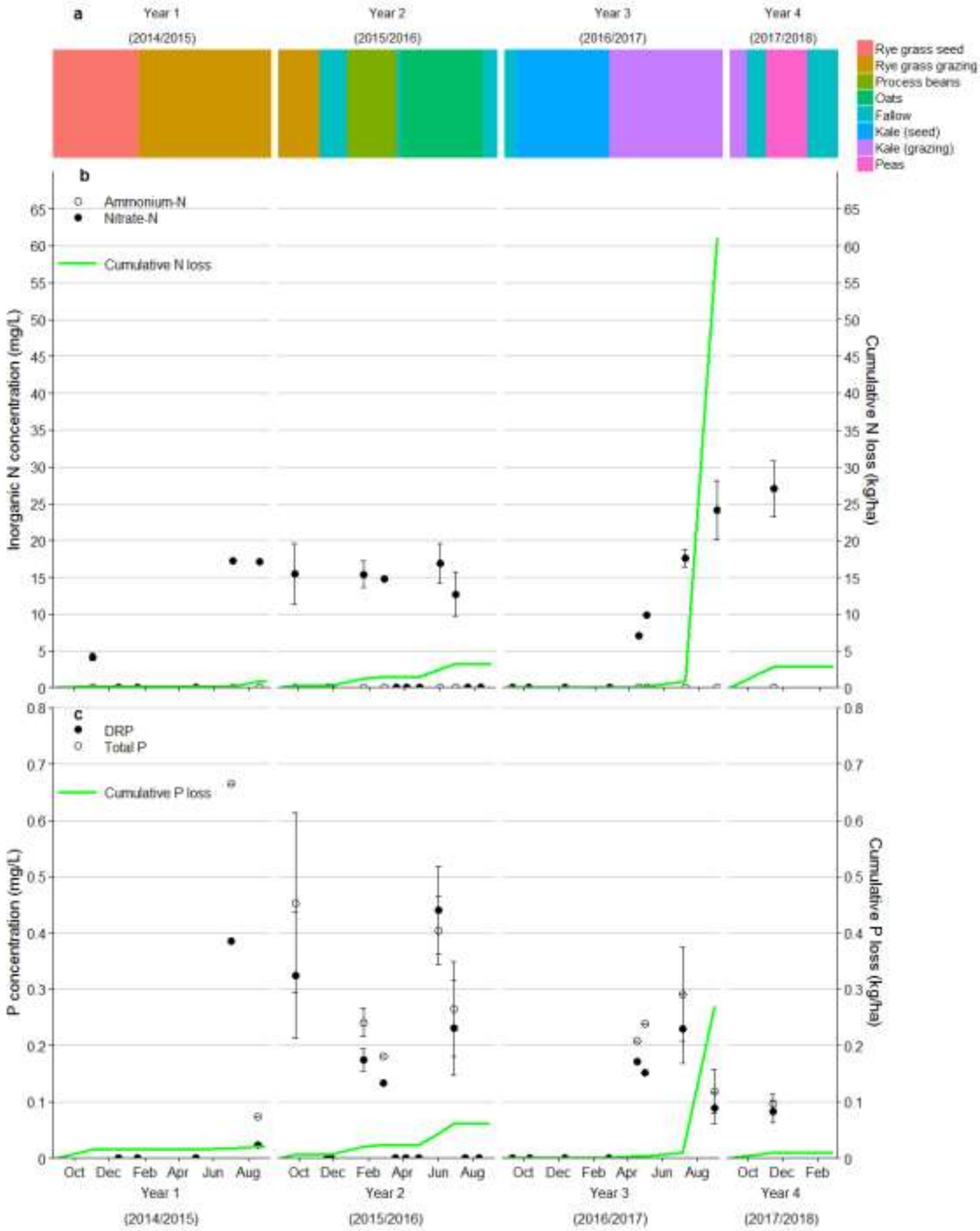

Figure 7. Sequence of crops (a), nitrate and ammonium concentrations and cumulative inorganic nitrogen (N) loss in drainage (b) and total phosphorus (P) and dissolved reactive phosphorus (DRP) concentrations and cumulative total P loss in drainage (c) at Site 3, Canterbury for the Year 1 (1 September 2014 to 30 August 2015), Year 2 (1 September 2015 to 30 August 2016), Year 3 (1 September 2016 to 30 August 2017) and current Year 4 (1 September 2017 to 28 February 2018) reporting periods. Bars around each point represent the standard error of the mean.

3.4 Site 4

3.4.1 Site overview

Site 4 is located near Levin on an intensive vegetable cropping enterprise. The soil type is a Shannon silt loam (*mottled argillic pallic*). Since installation of the fluxmeters in October 2014 there have been nine crop sequences including three lettuce crops, three successive crops of spinach, cabbage, zucchini and spring onions (the current crop) (see Figure 9a).

3.4.2 Site performance

Data from the past three and a half years indicates that the site is performing well with average measured drainage for the monitoring period (40 months) totalling 1654 mm, comparable to the 1769 mm predicted by the soil water balance model (Figure 8a). Both the timing of drainage events and patterns of accumulation were consistent with modelled predictions. During this time all 12 fluxmeters were effective at capturing drainage with cumulative totals ranging from 322 to 2951 mm (median = 1759 mm, CV = 48%; Appendix 2). The wide range in cumulative totals reflects different patterns of drainage accumulation across the site as affected by topography, soil physical and crop factors. There were 28 samplings (in only one of these was no drainage recorded) and the average number of samples used to calculate mean drainage volumes and nutrient losses 10.0 (range was 7 to 12).

Drainage tended to occur from late autumn (May/June) through to early summer (December/January) with volumes for respective Year 1, Year 2, Year 3 and the current Year 4 periods totalling 372, 354, 804 and 125 mm. High drainage volumes were consistent with regular rainfall events and the type of the cropping system which included shallow rooting crops with short rotations and multiple fallow periods. While precipitation input (rainfall + irrigation) data were collated from offsite weather sources until December 2017 (and during periods where logging equipment was removed to allow for management activity), the nearest NIWA climate station was only 2 km from the site (Appendix 1) ensuring that rainfall inputs were representative. Samples for soil physical and hydraulic characterisation were taken in April 2018 and results from these analysis will be incorporated into the model as they become available. The soil water retention curves used to parameterise the model are presented in Appendix 5a.

3.4.3 Nitrogen and phosphorus losses in drainage

Inorganic N losses were 641 kg/ha for the period 1 September 2014 to 28 February 2018 with respective Year 1, Year 2, Year 3 and current Year 4 period losses totalling 231, 142, 203 and 66 kg N/ha (Figure 9b). Nitrate-N was the predominant form of inorganic N in captured drainage with concentrations averaging 42.6 mg/L over the monitoring period (range in mean concentrations was 16.6–84.9 mg/L). High losses of inorganic N reflect a combination of high drainage volumes and high concentrations of nitrate-N in drainage water. A histogram of nitrate-N concentrations in drainage is provided in Appendix 3a.

Total P losses were 1.42 kg/ha for the period 1 September 2014 to 28 February 2018 with respective Year 1, Year 2, Year 3 and current Year 4 period losses totalling 0.45, 0.28, 0.68 and 0.07 kg P/ha (Figure 9c). These losses are considered to be low, reflecting primarily low concentrations of P in drainage water. Total P and DRP concentrations were comparably high over the Year 1 period (0.39 and 0.27 mg/L respectively) reflecting a soil settling effect following installation of the fluxmeters. Thereafter concentrations steadily decreased averaging 0.13 and

0.11 mg/L for respective total P and DRP fractions. A histogram of total P concentrations in drainage is provided in Appendix 4a.

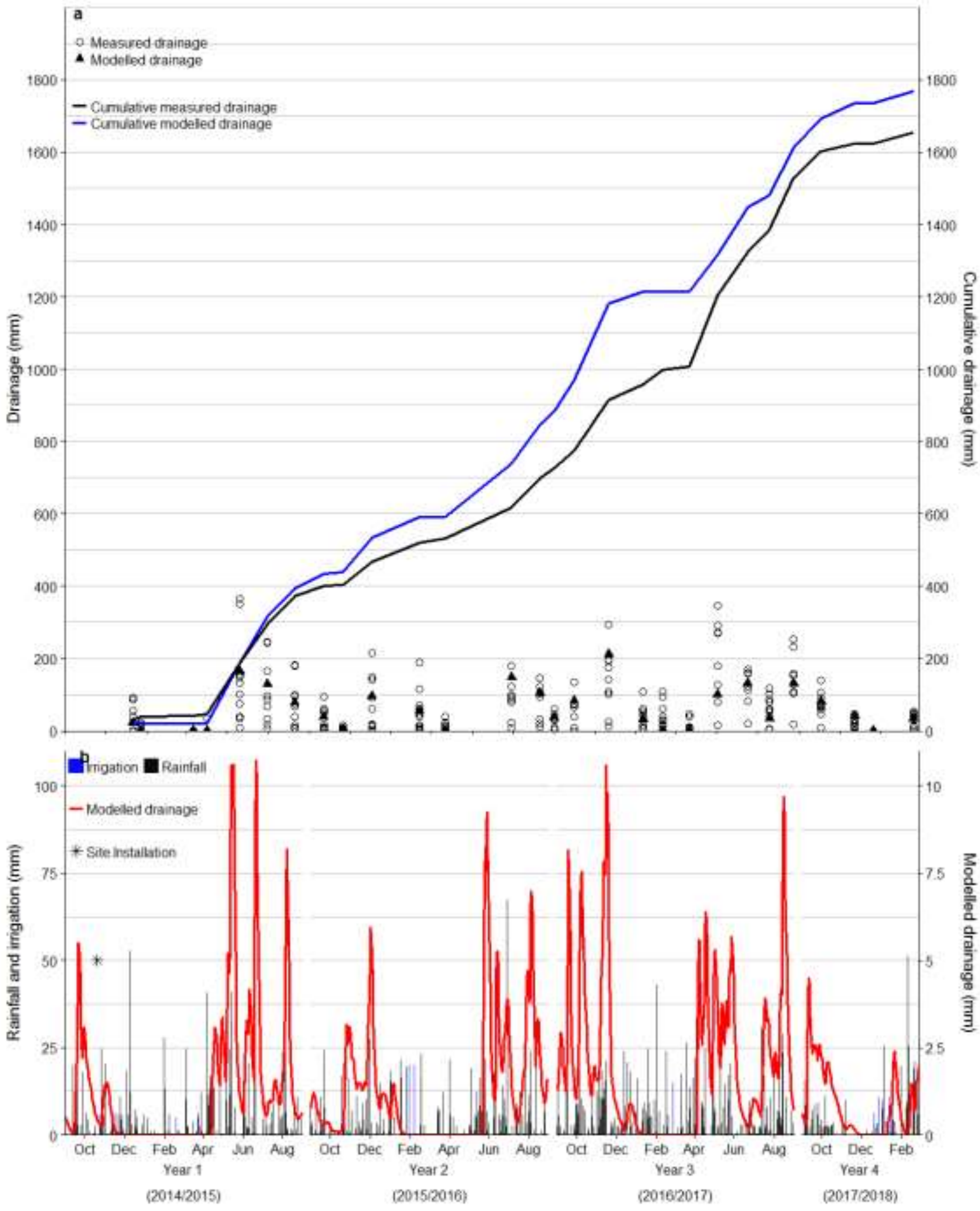

Figure 8. Comparison of measured and modelled drainage data (including drainage volumes for each of the 12 individual fluxmeter units) (a) in conjunction with rainfall and irrigation inputs and modelled drainage at 100 cm (b) at Site 4, Manawatu for the Year 1 (1 September 2014 to 30 August 2015), Year 2 (1 September 2015 to 30 August 2016), Year 3 (1 September 2016 to 30 August 2017) and current Year 4 (1 September 2017 to 28 February 2018) reporting periods. Modelled data were generated using the mechanistic Soil-Plant-Atmospheric-Model (SPASMO).

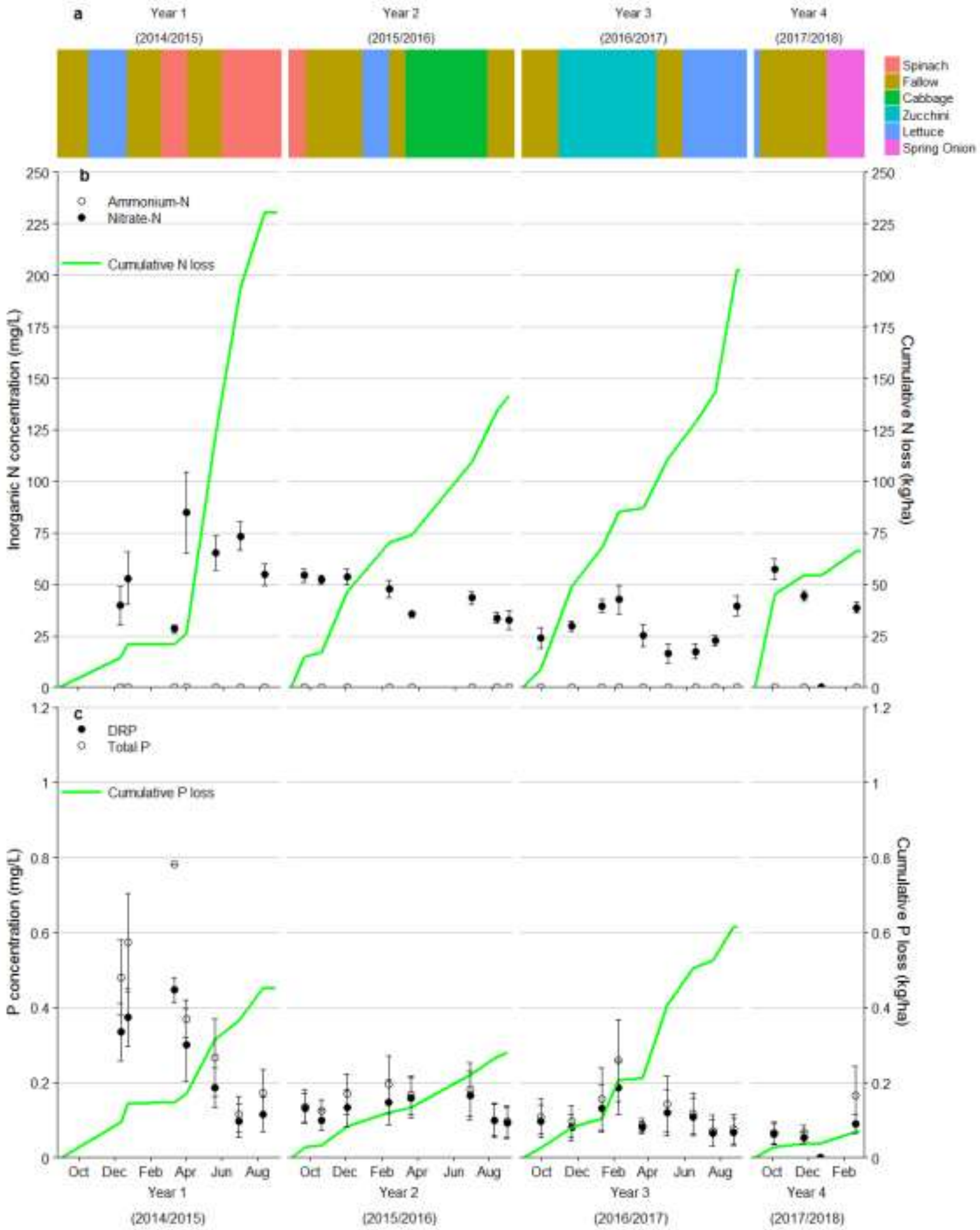

Figure 9. Sequence of crops (a), nitrate and ammonium concentrations and cumulative inorganic nitrogen (N) loss in drainage (b) and total phosphorus (P) and dissolved reactive phosphorus (DRP) concentrations and cumulative total P loss in drainage (c) at Site 4, Manawatu for the Year 1 (1 September 2014 to 30 August 2015), Year 2 (1 September 2015 to 30 August 2016), Year 3 (1 September 2016 to 30 August 2017) and current Year 4 (1 September 2017 to 28 February 2018) reporting periods. Bars around each point represent the standard error of the mean.

3.5 Site 5

3.5.1 Site overview

Site 5 is located near Bulls on a mixed cropping and livestock grazing enterprise. The soil type is a Pukepuke sandy loam (*typic sandy gley*). Since installation of the fluxmeters in September 2014 there have been five crop sequences including fodder beet, seed oats, forage oats and two crops of maize (the current crop) (see Figure 11a).

3.5.2 Site performance

Data from the past three and a half years indicates that the site is performing well with average measured drainage for the monitoring period (41 months) totalling 1951 mm, comparable to the 2048 mm predicted by the soil water balance model (Figure 10a). Both the timing of drainage events and patterns of accumulation were consistent with modelled predictions. During this time, all 12 fluxmeters were effective at capturing drainage with cumulative totals ranging from 584 to 3323 mm (median = 1948 mm, CV = 57%; Appendix 2). The wide range in cumulative totals reflects different patterns of drainage accumulation across the site as affected by topography, soil physical and crop factors. There were 29 samplings and the average number of samples used to calculate mean drainage volumes and nutrient losses was 9.8 (range was 7 to 12).

Drainage occurred at regular intervals through the year except for the late summer to early autumn period (February to March) when rainfall inputs were reduced and crop water requirements increased (Figure 10b). Captured volumes for respective Year 1, Year 2, Year 3 and the current Year 4 periods totalled 643, 476, 622 and 160 mm. High drainage volumes were consistent with high inputs from rainfall and summer irrigation (Figure 10b) in conjunction with the low soil water holding capacity of the Pukepuke sandy loam. Rainfall and irrigation data were collated from offsite sources (Appendix 1) until October 2017 and during periods where logging equipment was removed to allow for management activity. Soil samples for physical and hydraulic characterisation were taken in September 2017 and results from these analyses were used to parameterise the soil water balance model (Appendix 5a).

3.5.3 Nitrogen and phosphorus losses in drainage

Inorganic N losses were 540 kg/ha for the period 1 September 2014 to 28 February 2018 with respective Year 1, Year 2, Year 3 and current Year 4 period losses totalling 234, 84, 143 and 79 kg N/ha (Figure 11b). Nitrate-N was the predominant form of inorganic N in captured drainage with concentrations averaging 26.9 mg/L over the monitoring period (range in mean concentrations was 3.1–80.1 mg/L). A distinct seasonal pattern for nitrate concentration was observed with concentrations tending to peak in mid to late summer before declining over the autumn through to winter and spring periods. High losses of inorganic N reflected a combination of high drainage volumes (winter/spring losses) and high concentrations of nitrate-N in drainage water (summer/autumn losses). A histogram of nitrate-N concentrations in drainage is provided in Appendix 3a.

Total P losses were 1.23 kg/ha for the period 1 September 2014 to 28 February 2018 with respective Year 1, Year 2, Year 3 and current Year 4 period losses totalling 0.52, 0.25, 0.37 and 0.09 kg P/ha (Figure 11c). These losses are considered to be low, reflecting primarily low concentrations of P in drainage water. Total P and DRP concentrations were comparably high in the 6 months following installation (0.30 and 0.18 mg/L respectively) reflecting a soil settling effect. Thereafter, concentrations steadily decreased averaging 0.057 and 0.056 mg/L for respective tot P and DRP fractions. A histogram of total P concentrations in drainage is provided in Appendix 4a.

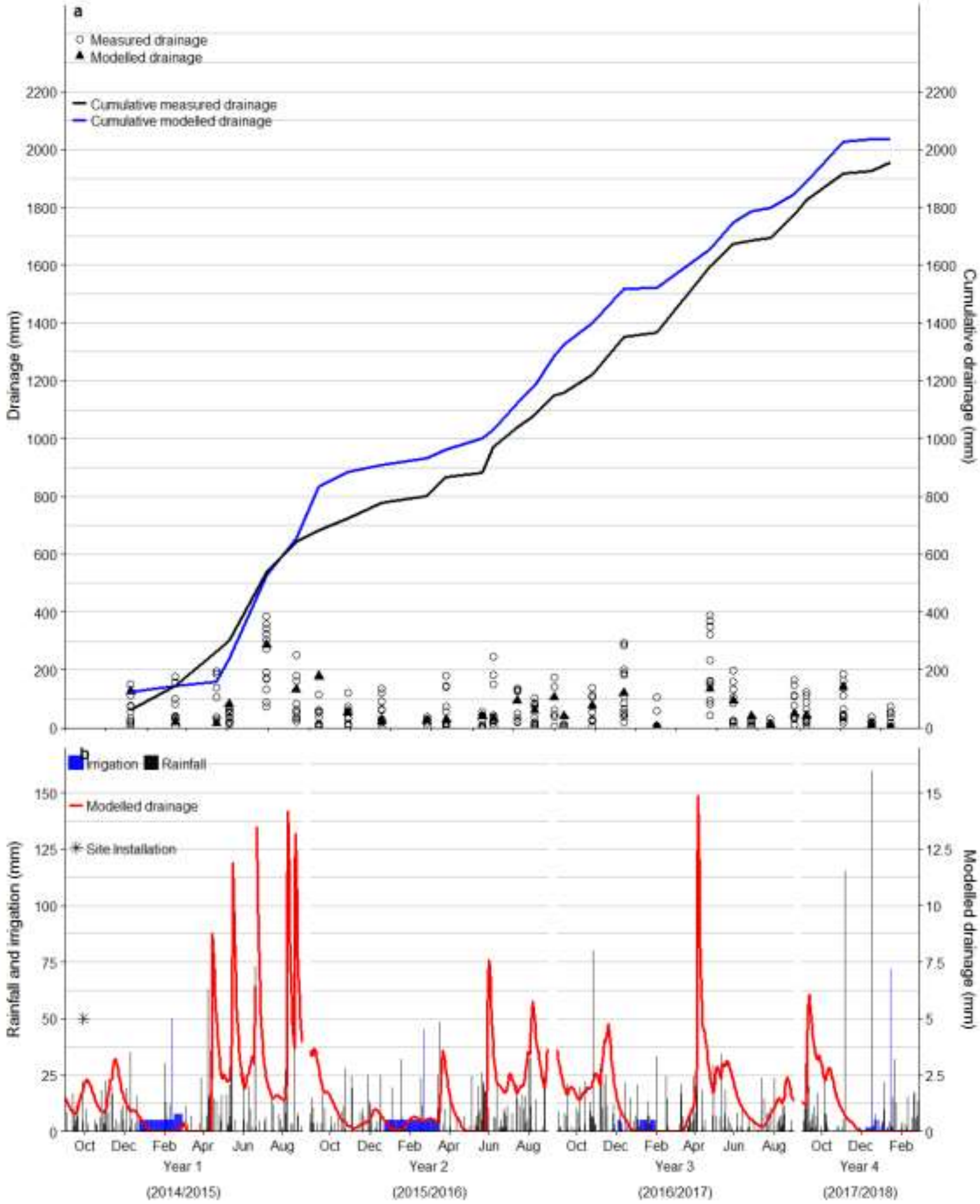

Figure 10. Comparison of measured and modelled drainage data (including drainage volumes for each of the 12 individual fluxmeter units) (a) in conjunction with rainfall and irrigation inputs and modelled drainage at 100 cm (b) at Site 5, Manawatu for the Year 1 (1 September 2014 to 30 August 2015), Year 2 (1 September 2015 to 30 August 2016), Year 3 (1 September 2016 to 30 August 2017) and current Year 4 (1 September 2017 to 28 February 2018) reporting periods. Modelled data were generated using the mechanistic Soil-Plant-Atmospheric-Model (SPASMO).

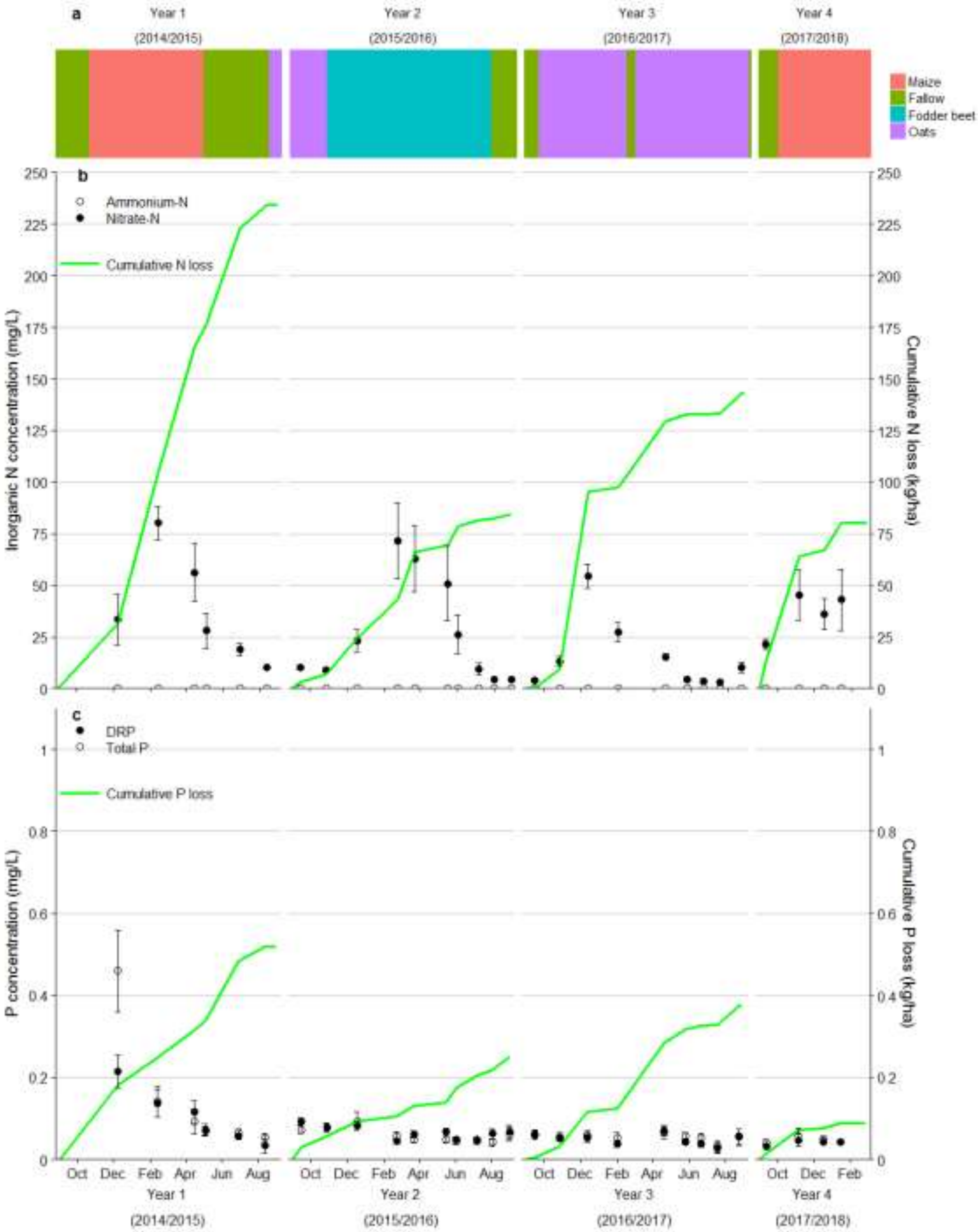

Figure 11. Sequence of crops (a), nitrate and ammonium concentrations and cumulative inorganic nitrogen (N) loss in drainage (b) and total phosphorus (P) and dissolved reactive phosphorus (DRP) concentrations and cumulative total P loss in drainage (c) at Site 5, Manawatu for the Year 1 (1 September 2014 to 30 August 2015), Year 2 (1 September 2015 to 30 August 2016), Year 3 (1 September 2016 to 30 August 2017) and current Year 4 (1 September 2017 to 28 February 2018) reporting periods. Bars around each point represent the standard error of the mean.

3.6 Site 6

3.6.1 Site overview

Site 6 is located near Ohakune on a mixed cropping and livestock grazing enterprise. The soil type is an Ohakune brown loam (*typic orthic allophanic*). Since installation of the fluxmeters in April 2015 there have been three crop sequences including two successive crops of winter wheat followed by rye grass for grazing (the current crop) (see Figure 13a).

3.6.2 Site performance

Data from the past 3 years indicates that the site is performing well with average measured drainage for the monitoring period (34 months) totalling 1324 mm, comparable to the 1338 mm predicted by the soil water balance model (Figure 12a). In general, the timing of drainage events and patterns of accumulation were consistent with modelled predictions, although modelled drainage tended to be greater than measured values in the first year following installation (respective totals were 455 and 293 mm). This may reflect a soil settling effect following installation of the fluxmeters and/or the use of non-site specific rainfall and irrigation data. In March 2017, an onsite rain gauge logger was installed and soil samples taken for physical and hydraulic characterisation. Results from these soil analyses were used to parametrise the soil water balance model (Appendix 5 a). Captured volumes for respective Year 1 (only 5 months at this site), Year 2, Year 3 and the current Year 4 periods totalled 219, 425, 484 and 194 mm with drainage occurring predominantly over the winter and spring periods.

Except for a period between June and November 2016, all 12 fluxmeters were effective at capturing drainage with cumulative totals ranging from 181 to 3072 mm (median = 1076 mm, CV = 71%; Appendix 2). In the aforementioned period, fluxmeter units 2 and 8 were deemed to be faulty (no drainage was collected despite modelled totals equalling 459 mm) and consequently these zero value were omitted from the analysis. The wide range in cumulative totals reflects different patterns of drainage accumulation across the site as affected by topography, soil physical and crop factors. There were 18 samplings and the average number of samples used to calculate mean drainage volumes and nutrient losses was 10.8 (range was 8 to 12).

3.6.3 Nitrogen and phosphorus losses in drainage

Inorganic N losses were 140 kg/ha for the period 1 September 2014 to 28 February 2018 with respective Year 1 (only 5 months at this site), Year 2, Year 3 and current Year 4 period losses totalling 50, 46, 31 and 14 kg N/ha (Figure 13b). Nitrate-N was the predominant form of inorganic N in captured drainage with concentrations averaging 10.1 mg/L over the monitoring period (range in mean concentrations was 3.4–22.5 mg/L). Inorganic N concentrations were generally low (Appendix 3a) and consequently losses were driven primarily by high drainage volumes over the winter and spring months.

Total P losses were 0.38 kg/ha for the period 1 September 2014 to 28 February 2018 with respective Year 1 (only 5 months at this site), Year 2, Year 3 and current Year 4 period losses totalling 0.19, 0.10, 0.06 and 0.02 kg P/ha (Figure 13c). Low losses reflect primarily low concentrations of P in drainage water with most P lost (0.18 kg P/ha) in the first event following installation of the fluxmeters. Excluding this event, total P and DRP concentrations averaged

0.028 and 0.021 mg/L. A histogram of total P concentrations in drainage is provided in Appendix 4a.

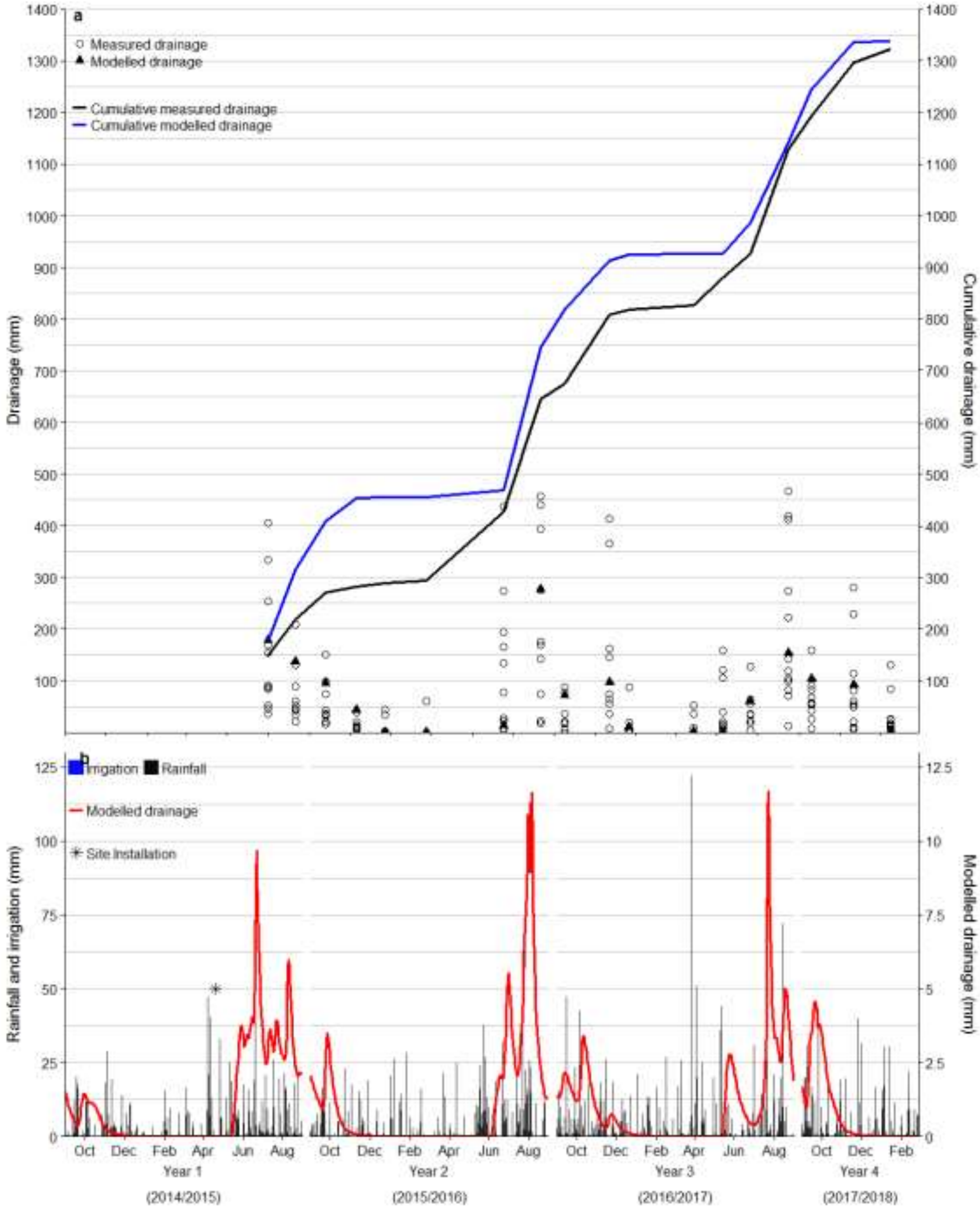

Figure 12. Comparison of measured and modelled drainage data (including drainage volumes for each of the 12 individual fluxmeter units) (a) in conjunction with rainfall and irrigation inputs and modelled drainage at 100 cm (b) at Site 6, Manawatu for the Year 1 (1 September 2014 to 30 August 2015), Year 2 (1 September 2015 to 30 August 2016), Year 3 (1 September 2016 to 30 August 2017) and current Year 4 (1 September 2017 to 28 February 2018) reporting periods. Modelled data were generated using the mechanistic Soil-Plant-Atmospheric-Model (SPASMO).

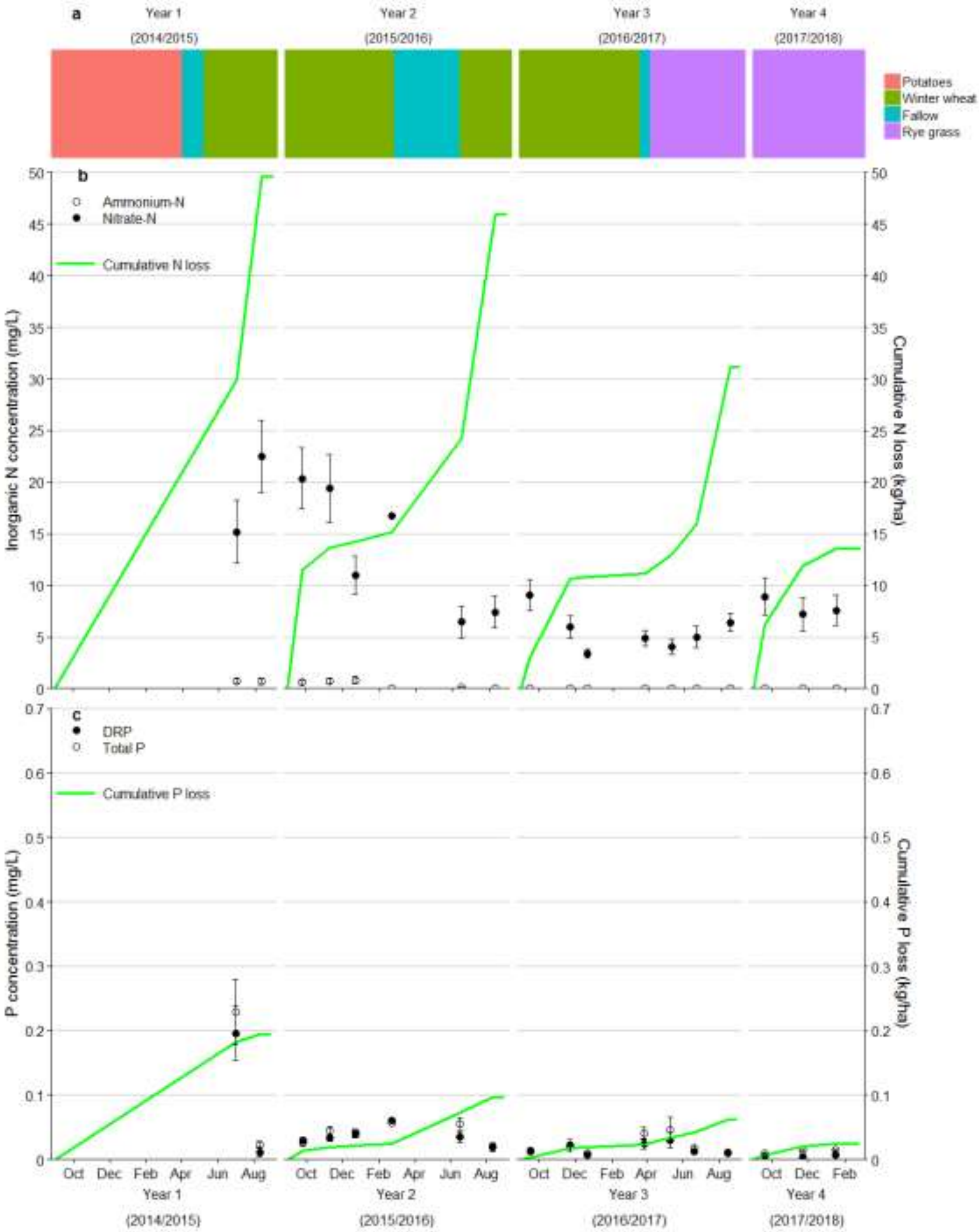

Figure 13. Sequence of crops (a), nitrate and ammonium concentrations and cumulative inorganic nitrogen (N) loss in drainage (b) and total phosphorus (P) and dissolved reactive phosphorus (DRP) concentrations and cumulative total P loss in drainage (c) at Site 6, Manawatu for the Year 1 (1 September 2014 to 30 August 2015), Year 2 (1 September 2015 to 30 August 2016), Year 3 (1 September 2016 to 30 August 2017) and current Year 4 (1 September 2017 to 28 February 2018) reporting periods. Bars around each point represent the standard error of the mean.

3.7 Site 7

3.7.1 Site overview

Site 7 is located near Otane on a mixed cropping and livestock grazing enterprise. The soil type is a Waimakariri silt loam (*weathered fluvial recent*). Since installation of the fluxmeters in September 2014 there have been eight crop sequences including carrots, two pea crops, process beans, barley and three winter rye grass crops (see Figure 15a).

3.7.2 Site performance

Average measured drainage for the monitoring period (41 months) totalled 1302 mm, considerably higher than the 410 mm predicted by the soil water balance model. This large discrepancy was related to site-wide flooding of the fluxmeter units between June and October 2017 (Figure 14a). Three flooding events occurred (June, July and October 2017) with the sum of captured drainage for these events totalling 1113 mm compared to 214 mm predicted by the model. Flooding was the likely result of exfiltration from groundwater intrusion following the water table rise after periods of sustained rainfall. We note that rainfall for the late summer to mid-autumn period (February to April) totalled 385 mm, 255% higher than the long-term average for this period (151 mm). This meant that the soil profile was already saturated going into the usual winter and spring drainage period.

Apart from flooding events, average measured drainage compared favourably with modelled outputs with respect to both the timing of drainage events and patterns of accumulation (Figure 14a). Captured drainage volumes remained modest for the first two and a half years (September 2014 to April 2017) totalling 92 mm (modelled total was 123 mm) before the large drainage events in winter/spring 2017. Most drainage during the monitoring period occurred over the late winter and spring periods (Figure 14b).

All 12 fluxmeters were effective at capturing drainage with cumulative drainage totals ranging from 998 to 1597 mm (median = 1550 mm, CV = 31%; Appendix 2). The wide range in these totals reflects in part the inclusion of outlier values including the data for the three flooding events. Substituting flooding event data with modelled drainage estimates, cumulative drainage totals ranged from 278 to 660 mm (median = 382 mm, CV = 35%). The average number of samples used to calculate mean drainage volumes and nutrient losses (excluding data from flooding events) was 11.1 (range was 7 to 12). Rainfall and irrigation data were collated from offsite sources (Appendix 1) until February 2017 and during periods where logging equipment was removed to allow for management activity. Samples for soil physical and hydraulic characterisation were taken in March 2018 and results from these analyses will be incorporated into the water balance model as they become available. The soil water retention curves used to parameterise the model are presented in Appendix 5b.

3.7.3 Nitrogen and phosphorus losses in drainage

Inorganic N and tot P losses for the flooding events in June, July and October 2017 were calculated using a combination of modelled drainage volumes and measured concentration data. Nitrate concentrations for these events remained comparatively high (19.7, 17.0 and 32.4 mg/L; Figure 15b) indicating that at least some of this drainage originated from the overlying soil profile. Nevertheless, a considerable proportion was likely derived from groundwater infiltration and consequently, **data for these three events should be interpreted with caution**.

Inorganic N losses were 69 kg/ha for the period 1 September 2014 to 28 February 2018 with respective Year 1 and Year 2 losses totalling 2.0 and 1.2 kg N/ha and respective Year 3 and current Year 4 period losses estimated at 46 and 20 kg N/ha (Figure 15 b). Nitrate-N was the predominant form of inorganic N in captured drainage with concentrations averaging 15.8 mg/L over the monitoring period (range in mean concentrations was 4.5–32.4 mg/L). A histogram of nitrate-N concentrations in drainage is provided in Appendix 3b.

Total P losses were 0.78 kg/ha for the period 1 September 2014 to 28 February 2018 with respective Year 1 and Year 2 losses totalling 0.07 and 0.03 kg P/ha and respective Year 3 and current Year 4 period losses estimated at 0.56 and 0.10 kg P/ha (Figure 15c). A histogram of total P concentrations in drainage is provided in Appendix 4b.

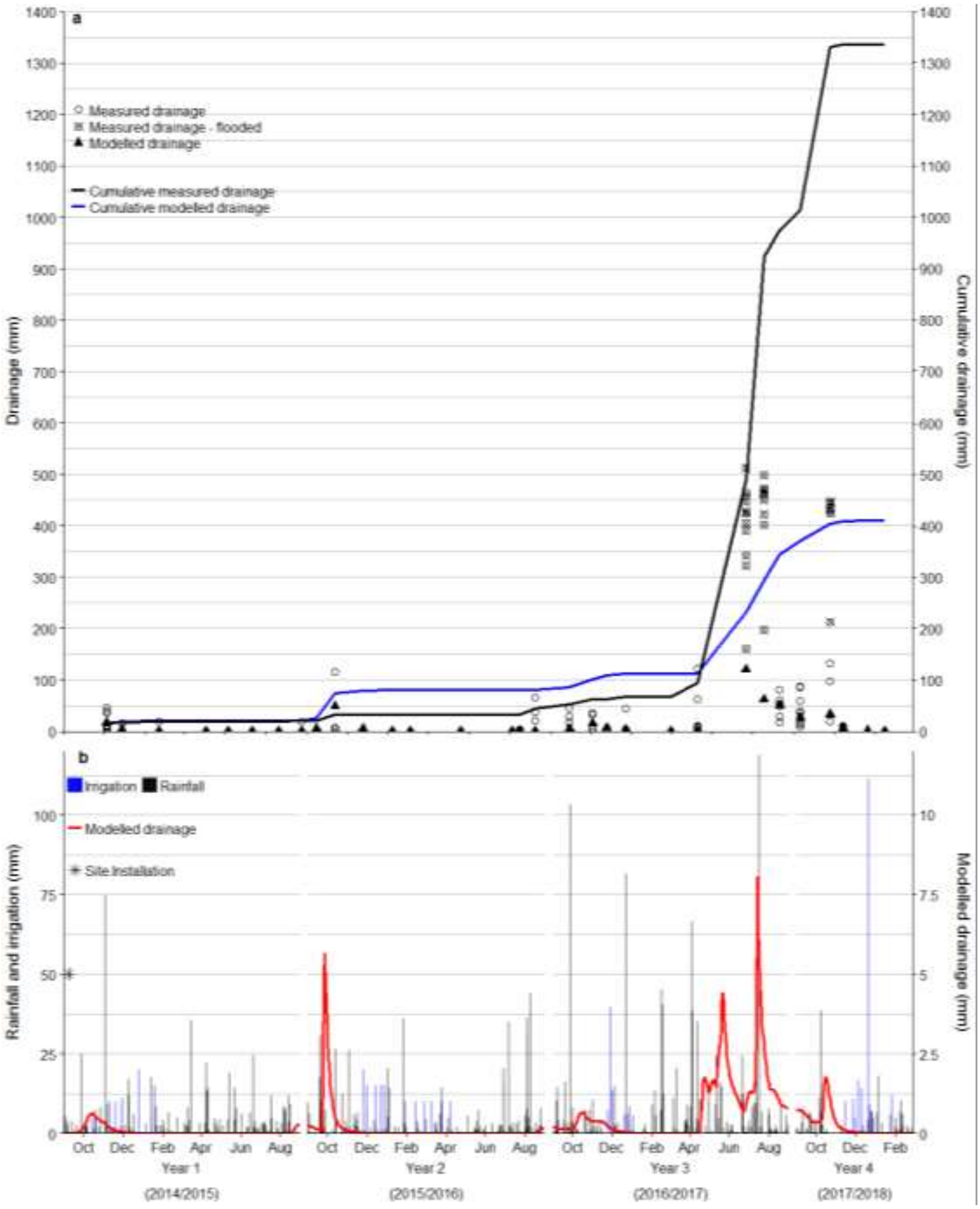

Figure 14. Comparison of measured and modelled drainage data (including drainage volumes for each of the 12 individual fluxmeter units) (a) in conjunction with rainfall and irrigation inputs and modelled drainage at 100 cm (b) at Site 7, Hawke's Bay for the Year 1 (1 September 2014 to 30 August 2015), Year 2 (1 September 2015 to 30 August 2016), Year 3 (1 September 2016 to 30 August 2017) and current Year 4 (1 September 2017 to 28 February 2018) reporting periods. Modelled data were generated using the mechanistic Soil-Plant-Atmospheric-Model (SPASMO).

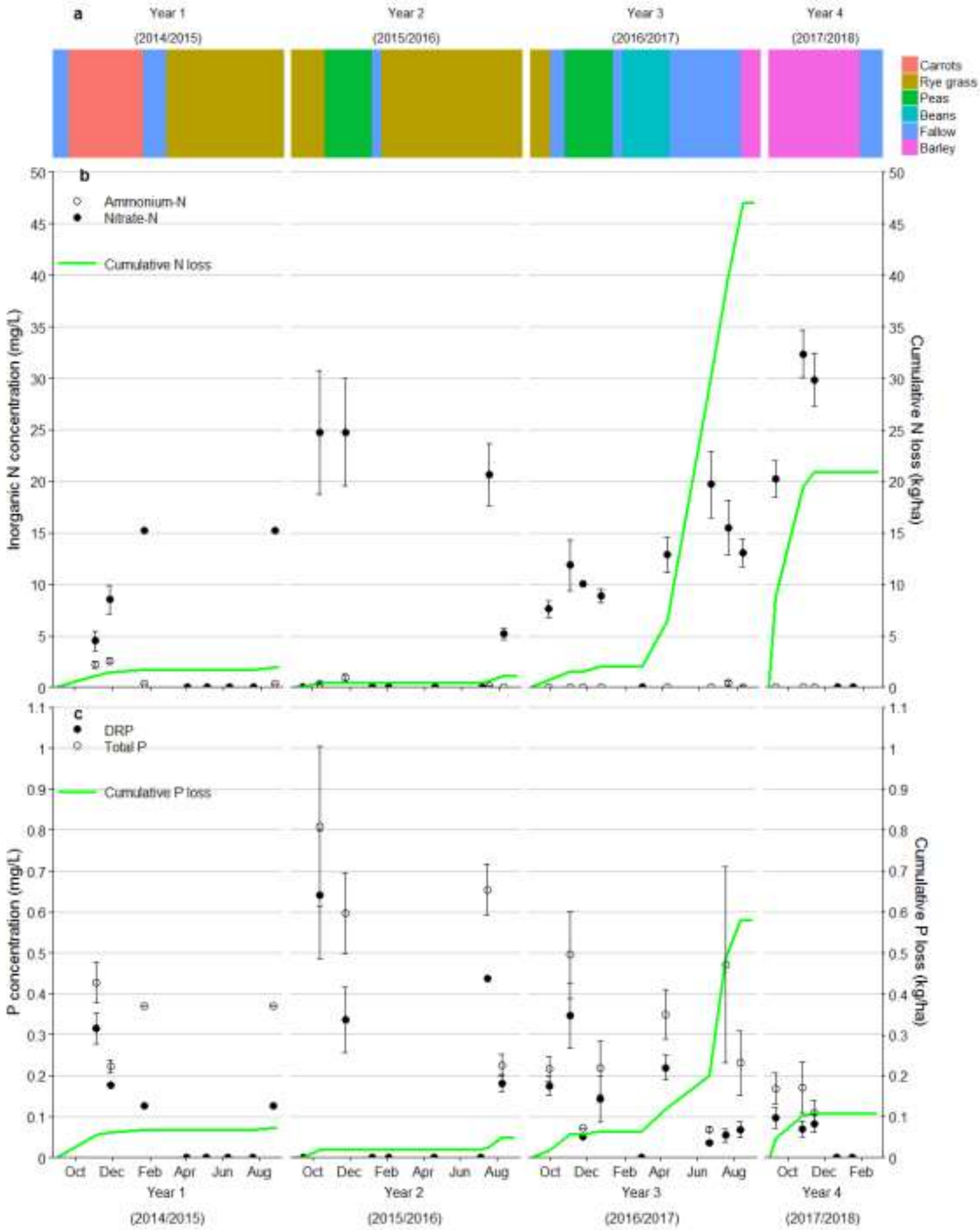

Figure 15. Sequence of crops (a), nitrate and ammonium concentrations and cumulative inorganic nitrogen (N) loss in drainage (b) and total phosphorus (P) and dissolved reactive phosphorus (DRP) concentrations and cumulative total P loss in drainage (c) at Site 7, Hawke's Bay for the Year 1 (1 September 2014 to 30 August 2015), Year 2 (1 September 2015 to 30 August 2016), Year 3 (1 September 2016 to 30 August 2017) and current Year 4 (1 September 2017 to 28 February 2018) reporting periods. Bars around each point represent the standard error of the mean. Year 3 and 4 cumulative totals include sampling events where losses were calculated using modelled drainage data and measured concentrations.

3.8 Site 8

3.8.1 Site overview

Site 8 is located near Hastings on a mixed cropping and livestock grazing enterprise. The soil type is a Waimakariri silt loam (*weathered fluvial recent*). Since installation of the fluxmeters in September 2014 there have been eight crop sequences including two crops of sweetcorn, two crops of tomatoes and four winter rye grass crops (see Figure 17a).

3.8.2 Site performance

Average measured drainage for the monitoring period (41 months) totalled 74 mm, some 57% less than the 171 mm predicted by the soil water balance model (Figure 16a). There is concern that a number of the fluxmeter units are not operating effectively, while those which are appear to be collecting more drainage than is being predicted by the model. There have been only been two periods of drainage collection to date, one in July and August 2016 and the other in June and July 2017. In the first, an average of 565 mm was collected from four units (all located in one cluster) while none was collected from the remaining eight units (Figure 16a). At the time these data were initially excluded from analysis under the premise that bypass flow may have occurred (average nitrate concentrations were very low at 0.93 mg/L). Up to this point, there was very little drainage predicted by the model (6 mm), consistent with drier than average seasonal conditions (respective rainfall totals for the Year 1 and 2 periods were 8 and 16% lower than long term averages) and two successive crops of summer sweetcorn which depleted soil moisture levels to a greater depth. The second period of drainage occurred in June and July 2017 in accordance with modelled predictions (Figure 16a and b), however, captured volumes were again highly variable with 378 mm collected from the aforementioned four units and an average of 21 mm collected from the remaining eight units. Of these eight units, six had zero drainage. Most concerning is the fact that five of the fluxmeter units have yet to register any drainage since installation in September 2014. Cumulative drainage totals for each fluxmeter ranged from 0 to 1352 mm (median = 84 mm, CV = 134%) (Appendix 2). These values represent 20 samplings, 15 of which had no drainage recorded.

Given the highly variable drainage volumes and questions over the performance of the fluxmeter units, we have limited confidence in drainage data from this site. It is possible the very dry Year 1 and Year 2 periods delayed fluxmeter ‘settling-in processes’ into Year 3 (drainage through the soil profile is required for this). In their study on the performance of fluxmeters across different soil types, Gee et al. (2009) found that in finer textured soils, passive wick fluxmeters perform best under higher drainage fluxes (> 100 mm/year) which have yet to be observed at this site. Consequently, the upcoming winter/spring rainfall period will be important for further informing the utility of this site. If a significant number of units continue to collect no drainage water reinstallation might be needed.

Rainfall and irrigation data were collated from offsite sources (Appendix 1) until November 2015 and during periods where logging equipment was removed to allow for management activity. Soil samples for physical and hydraulic characterisation were taken in March 2017 and results from these analyses were used to parameterise the soil water balance model (Appendix 5b).

3.8.3 Nitrogen and phosphorus losses in drainage

Inorganic N and total P losses could not be determined with confidence at this site due to poor drainage data including highly variable drainage volumes and uncertainty around the origins of the drainage captured in the fluxmeter units. For presentation purposes, N and P concentration data is presented in Figure 16. Due to the apparent failure of some the fluxmeters to capture drainage, the mean concentration values shown here only represent a small sample size (3 to 5 samples). Additionally, the low nitrate-N concentrations (average was 1.0 mg/L) and elevated total P concentrations (sample mean was 5.7 mg/l) indicate captured drainage likely entered the units through bypass flow.

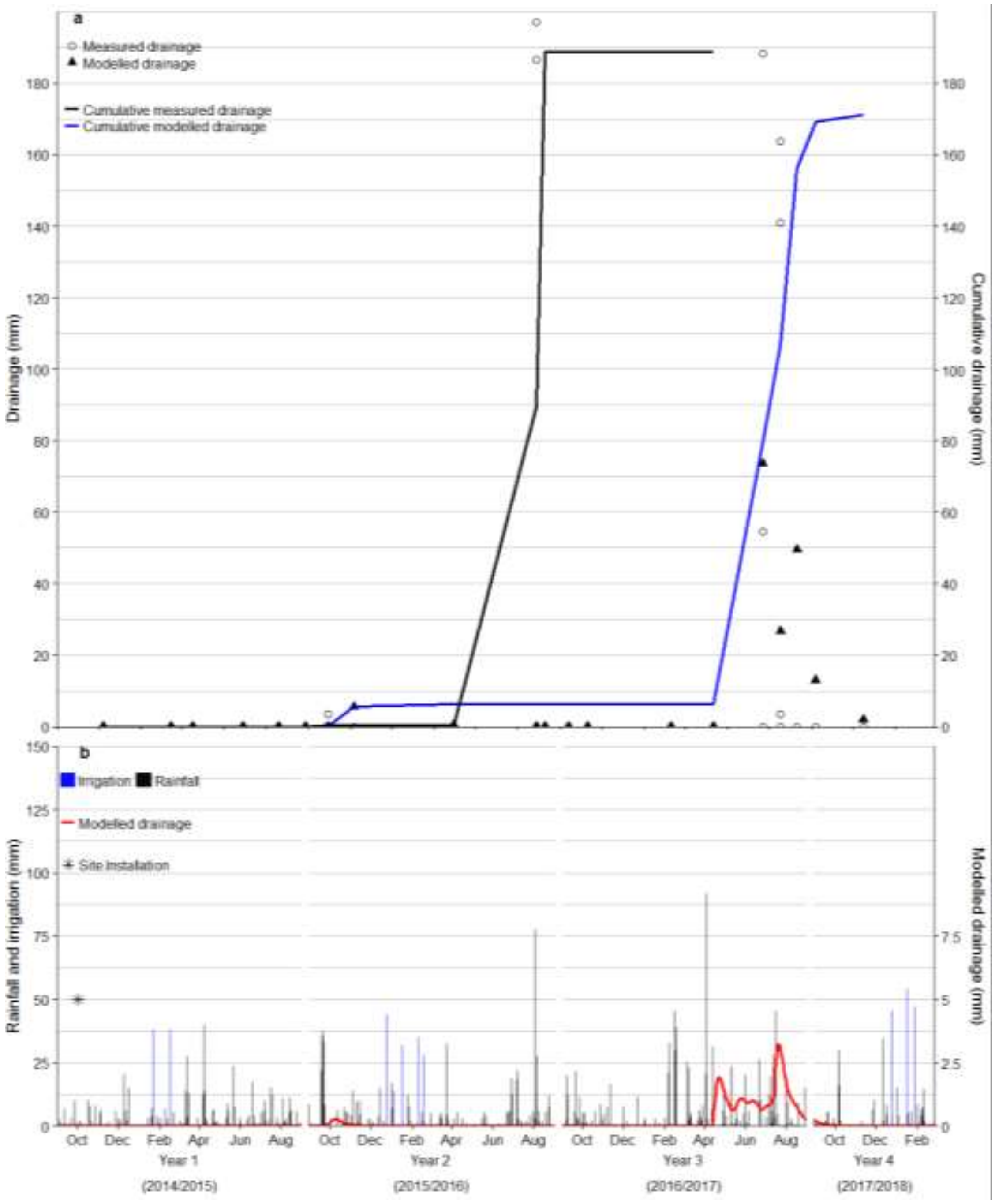

Figure 16. Comparison of measured and modelled drainage data (including drainage volumes for each of the 12 individual fluxmeter units) (a) in conjunction with rainfall and irrigation inputs and modelled drainage at 100 cm (b) at Site 8, Hawke's Bay for the Year 1 (1 September 2014 to 30 August 2015), Year 2 (1 September 2015 to 30 August 2016), Year 3 (1 September 2016 to 30 August 2017) and current Year 4 (1 September 2017 to 28 February 2018) reporting periods. Modelled data were generated using the mechanistic Soil-Plant-Atmospheric-Model (SPASMO).

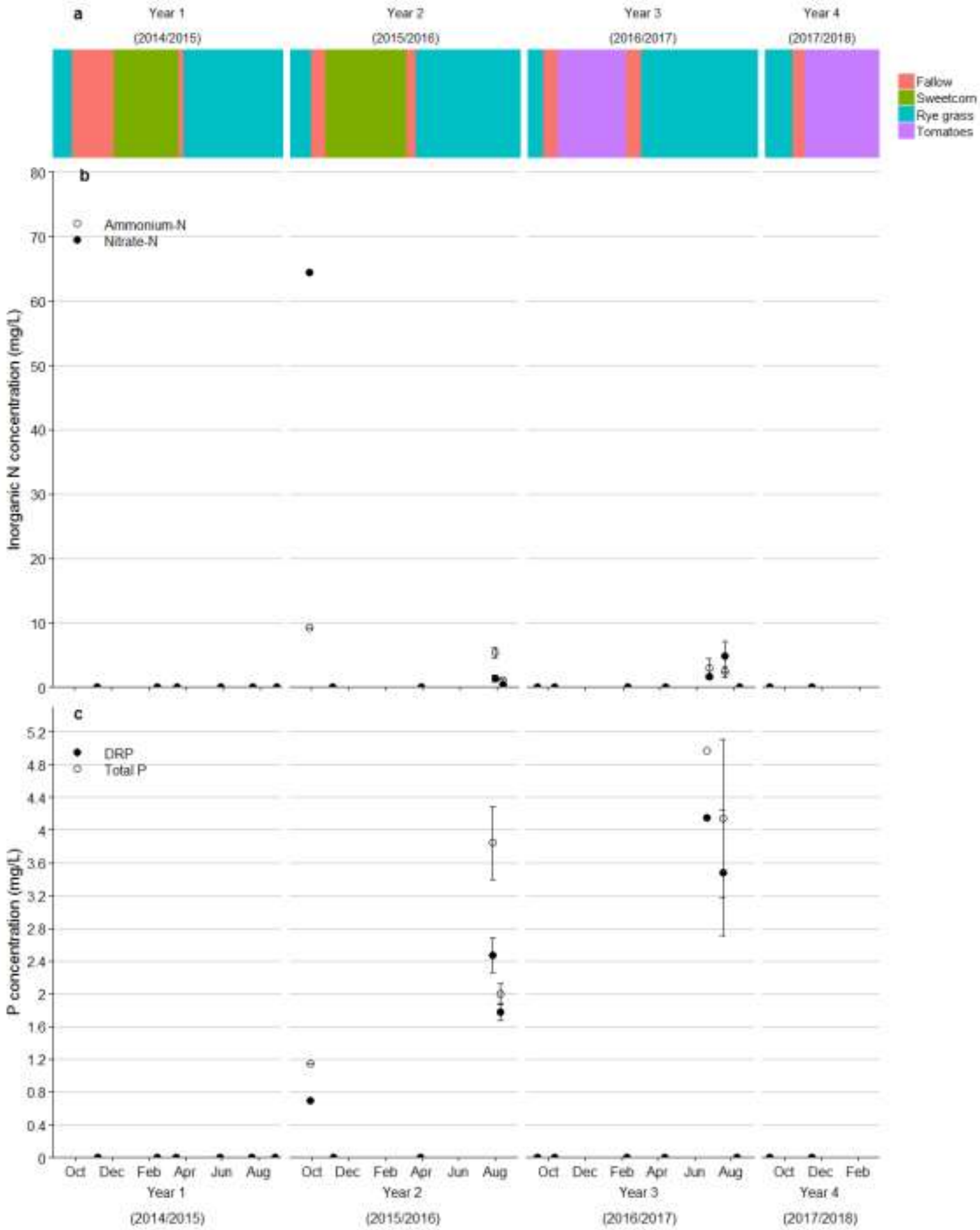

Figure 17. Sequence of crops (a), nitrate and ammonium concentrations and cumulative inorganic nitrogen (N) loss in drainage (b) and total phosphorus (P) and dissolved reactive phosphorus (DRP) concentrations and cumulative total P loss in drainage (c) at Site 8, Hawke's Bay for the Year 1 (1 September 2014 to 30 August 2015), Year 2 (1 September 2015 to 30 August 2016), Year 3 (1 September 2016 to 30 August 2017) and current Year 4 (1 September 2017 to 28 February 2018) reporting periods. Due to the apparent failure of some the fluxmeters to capture drainage, the mean concentration values shown here only represent a small sample size (3 to 5 samples). Bars around each point represent the standard error of the mean.

3.9 Site 9

3.9.1 Site overview

Site 9 is located near Takapau on a mixed cropping and livestock grazing enterprise. The soil type is a Takapau silt loam (*typic allophanic brown*). Since installation of the fluxmeters in September 2014 there have been eight crop sequences including two crops of peas, process beans, barley, rye grass seed, rye grass pasture and sorghum (see Figure 19a).

3.9.2 Site performance

Average measured drainage for the monitoring period (41 months) totalled 986 mm, 26% less than the 1329 mm predicted by the soil water balance model (Figure 18a). The general pattern of drainage accumulation was similar for modelled and measured values, with most drainage occurring through the winter and spring period (June to November). Captured volumes for respective Year 1, Year 2, Year 3 and the current Year 4 periods totalled 373, 115, 422 and 76 mm with drainage occurring predominantly over the winter and spring periods. Importantly, the measured drainage values reported here (Figure 18a) include outliers which were defined as being greater than 1.5 times the period rainfall (generally greater than 350 mm drainage). Excluding these high values resulted in very low drainage totals (464 mm over the monitoring period) which were considered unrealistic given the high precipitation inputs (4418 mm) and free draining, stony soil type. Nitrate concentrations for these outliers were comparable to concentrations from other samples with lower volumes (data not shown) indicating that this drainage most likely originated from the overlying soil profile and not from groundwater intrusion or bypass flow.

While including outlier values resulted in a more realistic total drainage value, captured volumes for each event were still generally less than modelled volumes, particularly in Years 2 and 3 (Figure 18a). This may in part be related to the use of non-site specific climate information, including rainfall and irrigation data which were collated from offsite sources (Appendix 1) until February 2017 and during periods where logging equipment was removed to allow for management activity. However, there may also be soil factors effecting the efficacy of drainage collection at this site, through, for example, a reduction in the matric suction of the fluxmeter units caused by a stony profile (stone content below 60 cm was estimated at 25 to 60%). A further evaluation of site performance will be undertaken when results from soil physical and hydraulic characterisation are incorporated into the water balance model (samples were taken in December 2017). Until then, these results should be interpreted with some caution. The soil water retention curves used to parameterise the model are presented in Appendix 5b.

Encouragingly, all 12 fluxmeters were effective at capturing drainage over the monitoring period with cumulative drainage totals ranging from 205 to 2629 mm (median = 795 mm, CV = 69%; Appendix 2). The wide range in cumulative totals likely reflects different patterns of drainage accumulation across the site as affected by topography, soil physical and crop factors in conjunction with the inclusion of outlier values for some of the units (e.g. units 4 and 7). There were 34 samplings (in 7 of these no drainage was recorded) and the average number of samples used to calculate mean drainage volumes and nutrient losses was 12 (outliers were included).

3.9.3 Nitrogen and phosphorus losses in drainage

Inorganic N losses were 79 kg/ha for the period 1 September 2014 to 28 February 2018 with respective Year 1, Year 2, Year 3 and current Year 4 period losses totalling 8, 24, 35 and 12 kg N/ha (Figure 19b). Nitrate-N was the predominant form of inorganic N in captured drainage with concentrations averaging 14.3 mg/L over the monitoring period (range in mean concentrations was 1.8–40.3 mg/L). Inorganic N losses were driven predominantly by high drainage volumes as opposed to high nitrate-N concentrations. A histogram of nitrate-N concentrations in drainage is provided in Appendix 3b.

Total P losses were 2.86 kg/ha for the period 1 September 2014 to 28 February 2018 with respective Year 1, Year 2, Year 3 and current Year 4 period losses totalling 1.99, 0.12, 0.67 and 0.09 kg P/ha (Figure 19c). Elevated losses in Year 1 likely reflect a soil settling effect following fluxmeter installation. Total P and DRP concentrations averaged 0.41 and 0.15 mg/L. A histogram of total P concentrations in drainage is provided in Appendix 4b.

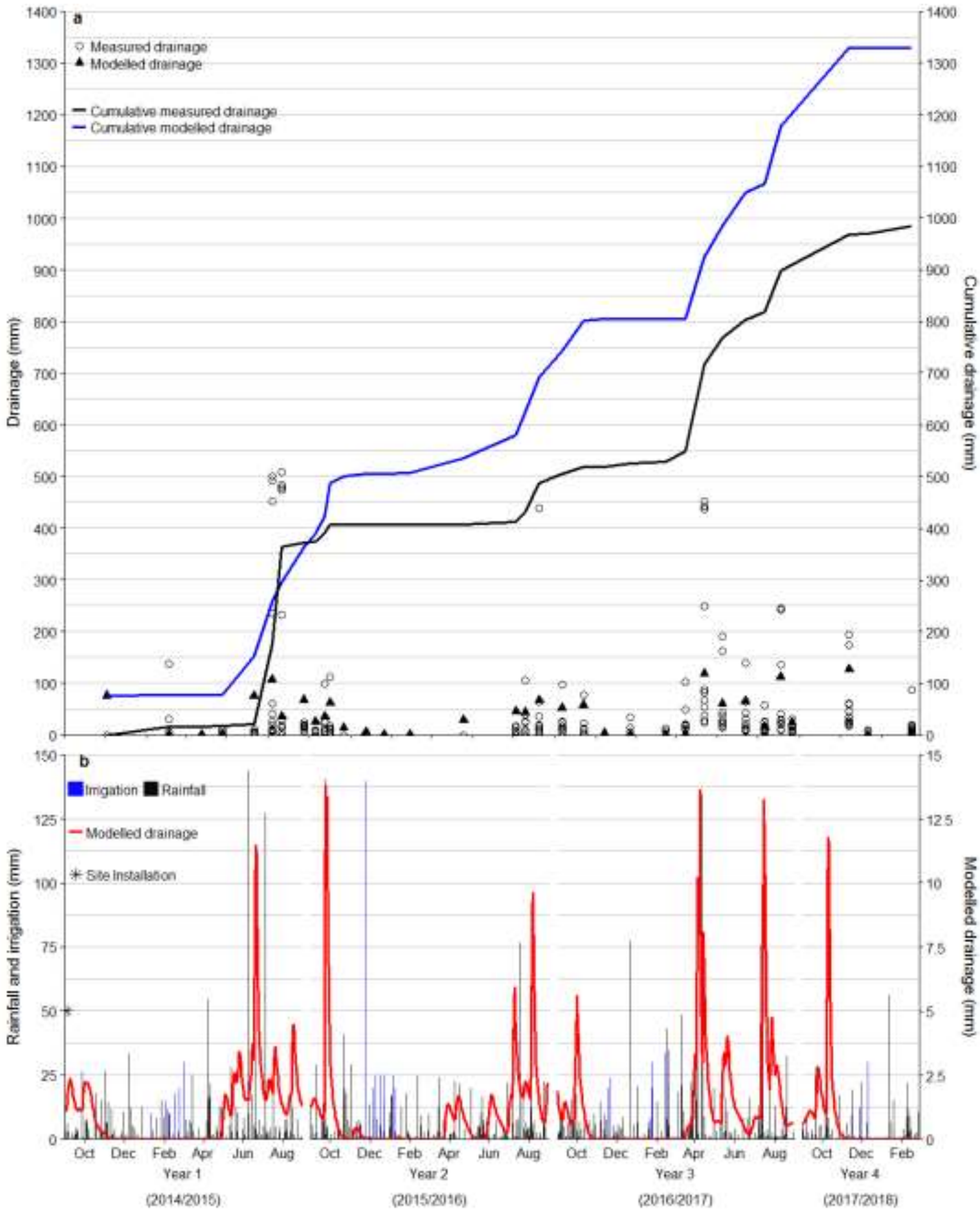

Figure 18. Comparison of measured and modelled drainage data (including drainage volumes for each of the 12 individual fluxmeter units) (a) in conjunction with rainfall and irrigation inputs and modelled drainage at 100 cm (b) at Site 9, Hawke's Bay for the Year 1 (1 September 2014 to 30 August 2015), Year 2 (1 September 2015 to 30 August 2016), Year 3 (1 September 2016 to 30 August 2017) and current Year 4 (1 September 2017 to 28 February 2018) reporting periods. Modelled data were generated using the mechanistic Soil-Plant-Atmospheric-Model (SPASMO).

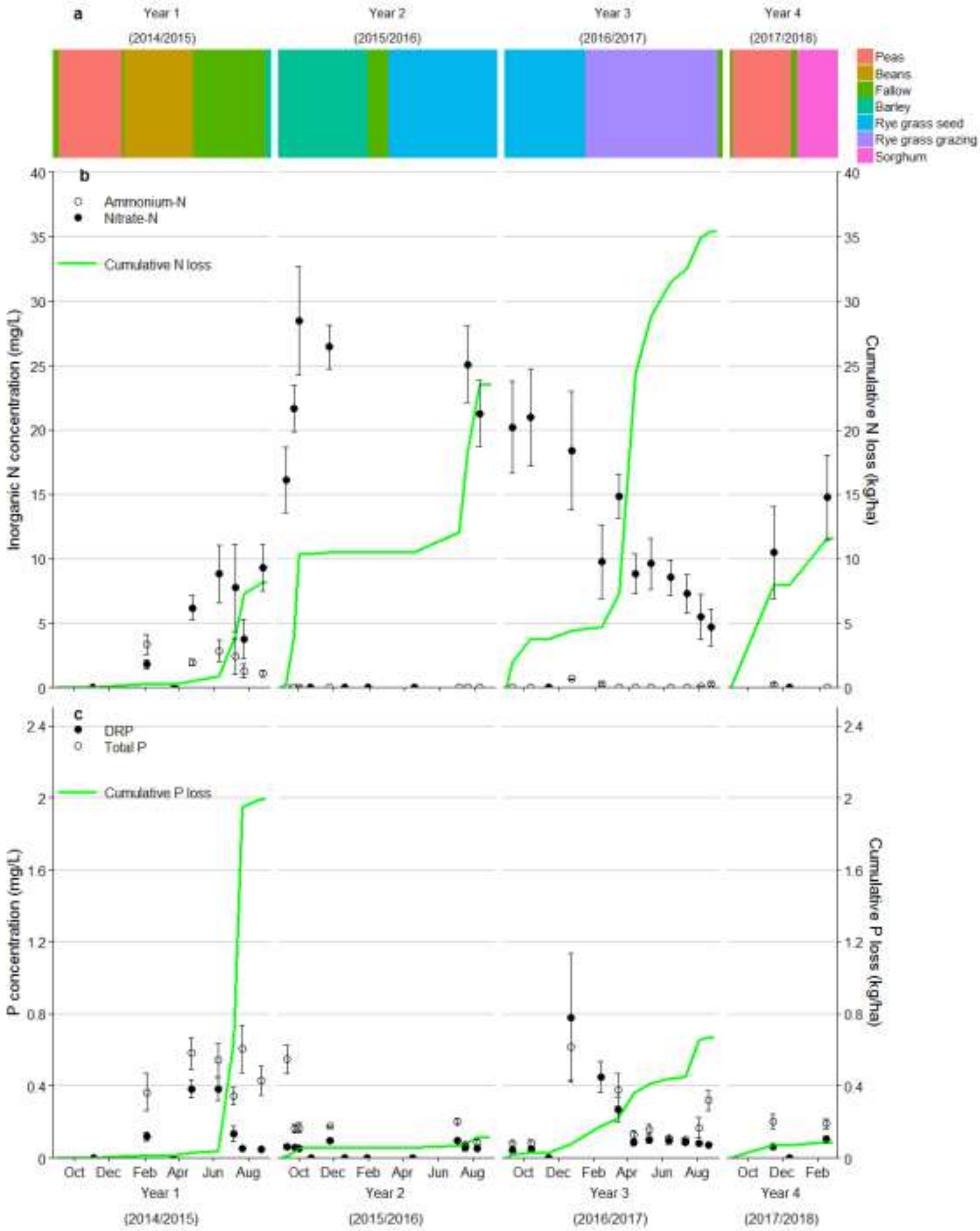

Figure 19. Sequence of crops (a), nitrate and ammonium concentrations and cumulative inorganic nitrogen (N) loss in drainage (b) and total phosphorus (P) and dissolved reactive phosphorus (DRP) concentrations and cumulative total P loss in drainage (c) at Site 9, Hawke's Bay for the Year 1 (1 September 2014 to 30 August 2015), Year 2 (1 September 2015 to 30 August 2016), Year 3 (1 September 2016 to 30 August 2017) and current Year 4 (1 September 2017 to 28 February 2018) reporting periods. Bars around each point represent the standard error of the mean.

3.10 Site 10

3.10.1 Site overview

Site 10 is located near Matamata on a mixed cropping and livestock grazing enterprise. The soil type a Waihou silt loam (*typic orthic allophanic*). Since installation of the fluxmeters in May 2015 there have been five crop sequences including two crops of winter rye grass, two potato crops and an onion crop (see Figure 21a).

3.10.2 Site performance

The site is performing satisfactorily. Average measured drainage for the monitoring period (33 months) totalled 916 mm, 19% less than the 1136 mm predicted by the soil water balance model (Figure 20a). Despite this discrepancy, both the timing of drainage events and patterns of accumulation were consistent with modelled predictions with drainage occurring predominantly through the winter and spring periods (June to November). Captured volumes for respective Year 1 (only 3 months at this site), Year 2, Year 3 and the current Year 4 periods totalled 148, 175, 508 and 85 mm.

For the first year following installation of the fluxmeters, all 12 units functioned well. However, in March 2016, units 9 and 11 were damaged by deep cultivation equipment rendering them ineffective for capturing drainage. Excluding these units, cumulative totals for the monitoring period ranged from 364 to 2005 mm (median = 913 mm, CV = 55%; Appendix 2). The wide range in cumulative totals reflects different patterns of drainage accumulation across the site as affected by topography, soil physical and crop factors. There were 24 samplings (in five of these no drainage was recorded) and the average number of samples used to calculate mean drainage volumes and nutrient losses was 9.6 (range was 9 to 11).

Rainfall and irrigation data were collated from offsite sources until August 2016 and during periods where logging equipment was removed to allow for management activity (Appendix 1). Soil samples for physical and hydraulic characterisation were taken in September 2017 and results these analyses were used to parameterise the soil water balance model (Appendix 5b).

3.10.3 Nitrogen and phosphorus losses in drainage

Inorganic N losses were 230 kg/ha for the period 1 September 2014 to 28 February 2018 with respective Year 1, Year 2, Year 3 and current Year 4 period losses totalling 34, 20, 171 and 5 kg N/ha (Figure 20b). Nitrate-N was the predominant form of inorganic N in captured drainage with concentrations averaging 15.5 mg/L over the monitoring period (range in mean concentrations was 8.9–42.9 mg/L). More than half of the total inorganic N loss (132 kg/ha) occurred between January and June 2017 following harvest of a summer onion crop. A histogram of nitrate-N concentrations in drainage is provided in Appendix 3b.

Total P losses were 0.30 kg/ha for the period 1 September 2014 to 28 February 2018 with respective Year 1, Year 2, Year 3 and current Year 4 period losses totalling 0.06, 0.05, 0.17 and 0.02 kg P/ha (Figure 20c). These losses are low, reflecting primarily low concentrations of total P in drainage water. Excluding the first drainage event in July 2015 which contained some sediment following installation of the units, total P and DRP concentrations averaged 0.04 and 0.02 mg/L. A histogram of total P concentrations in drainage is provided in Appendix 4b.

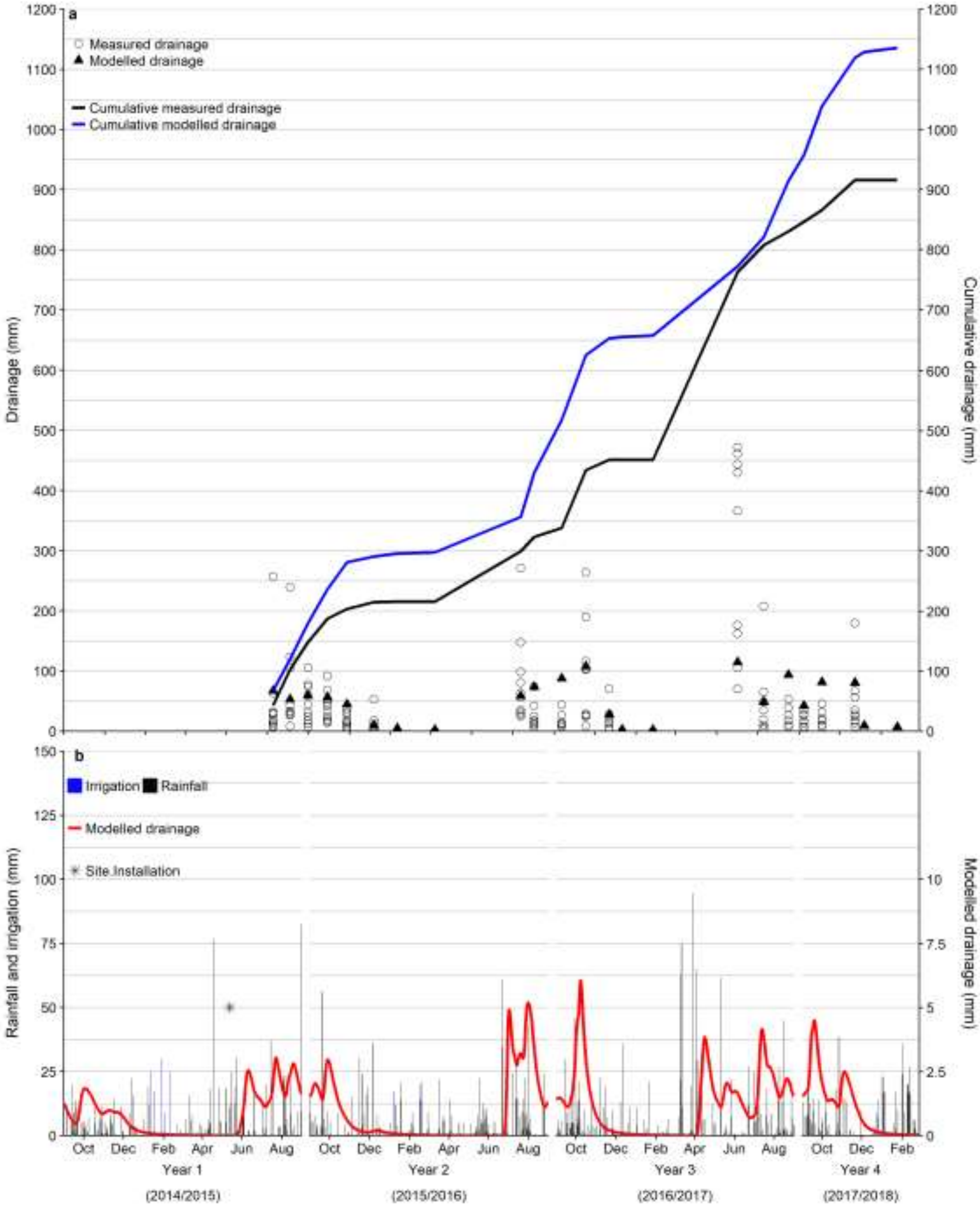

Figure 20. Comparison of measured and modelled drainage data (including drainage volumes for each of the 12 individual fluxmeter units) (a) in conjunction with rainfall and irrigation inputs and modelled drainage at 100 cm (b) at Site 10, Matamata for the Year 1 (1 September 2014 to 30 August 2015), Year 2 (1 September 2015 to 30 August 2016), Year 3 (1 September 2016 to 30 August 2017) and current Year 4 (1 September 2017 to 28 February 2018) reporting periods. Modelled data were generated using the mechanistic Soil-Plant-Atmospheric-Model (SPASMO).

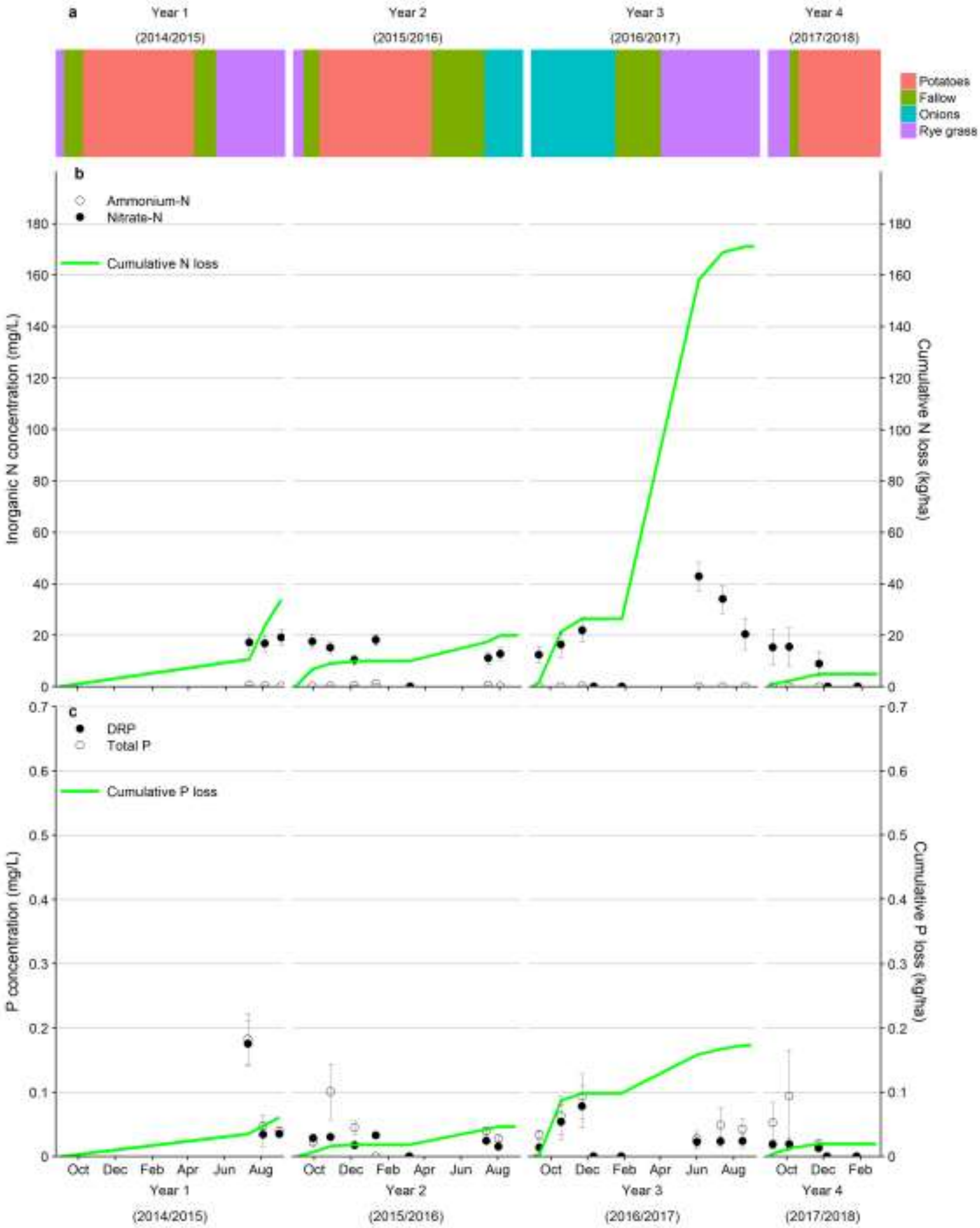

Figure 21. Sequence of crops (a), nitrate and ammonium concentrations and cumulative inorganic nitrogen (N) loss in drainage (b) and total phosphorus (P) and dissolved reactive phosphorus (DRP) concentrations and cumulative total P loss in drainage (c) at Site 10, Matamata for the Year 1 (1 September 2014 to 30 August 2015), Year 2 (1 September 2015 to 30 August 2016), Year 3 (1 September 2016 to 30 August 2017) and current Year 4 (1 September 2017 to 28 February 2018) reporting periods. Bars around each point represent the standard error of the mean.

3.11 Site 11

3.11.1 Site overview

Site 11 is located near Pukekohe on an intensive vegetable cropping enterprise. The soil type is a Patumahoe clay loam (*mottled orthic granular*). Since installation of the fluxmeters in May 2015 there have been three crop sequences including two crops of potatoes and one crop of onions (see Figure 23a).

3.11.2 Site performance

Average measured drainage for the monitoring period (33 months) totalled 4142 mm, 172 % higher than the 2407 mm predicted by the soil water balance model. This large discrepancy reflects flooding of the fluxmeter units during the first year and a half of the study (August 2015 to November 2016). Thereafter, there was better agreement between modelled and measured values with respective volumes totalling 1112 and 1278 mm for the period January 2017 to February 2018 (the cumulative total volumes in Figure 22a have been separated to reflect these two periods). Despite initial flooding of the fluxmeter units, both the timing of drainage events and patterns of accumulation were consistent with modelled predictions with drainage occurring predominantly through the late autumn to mid spring period (May to October).

Flooding of fluxmeters during the first year and a half was attributed to the creation of a ‘plug hole’ effect following installation of the fluxmeters through more compact subsoil. Consistent with this hypothesis was the rapid decrease in saturated hydraulic conductivity (Ksat) below the 40 cm depth (respective Ksat values for the 0–20, 20–40, 40–60, 60–80 and 80–1000 cm depths were 217, 26, 1.1, 1.1 and 0.7 mm/hr). While captured volumes during this period were unrealistic and not useful for quantifying losses, nitrate-N concentrations in drainage remained at moderate to high levels (19.0–49.9; Figure 23b) indicating that this drainage had permeated through the soil profile. Nutrient concentrations were, therefore, considered to be representative with losses in this period estimated using modelled drainage and measured concentrations (an approach that is common for other sampling methods such as suction cups).

To date, all 12 fluxmeters have been effective at capturing drainage with cumulative drainage in the period after January 2017, ranging from 866 to 1567 mm (median = 1337 mm, CV = 19%; Appendix 2). The wide range in cumulative totals reflects different patterns of drainage accumulation across the site as affected by topography, soil physical and crop factors. There were 19 samplings (in two of these no drainage was recorded) and the average number of samples used to calculate mean drainage volumes and nutrient losses in the period after January 2017 was 10.0 (range was 8–12). Rainfall and irrigation data were collated from offsite sources (Appendix 1) until November 2017 and during periods where logging equipment was removed to allow for management activity. Soil samples for physical and hydraulic characterisation were taken in February 2017 and results of these analyses were used to parameterise the soil water balance model (Appendix 5b).

3.11.3 Nitrogen and phosphorus losses in drainage

Inorganic N losses were estimated at 527 kg/ha for the period 1 September 2014 to 28 February 2018 with respective Year 1 (only 3 months at this site), Year 2, Year 3 and current Year 4 period losses totalling 45, 173, 192 and 118 kg N/ha (Figure 23b). **It is important to note that Year 1, 2 and 3 totals include sampling events where losses were calculated using modelled drainage data and measured concentrations and consequently these**

results should be interpreted with caution. Nitrate-N was the predominant form of inorganic N in captured drainage with concentrations averaging 24.4 mg/L over the monitoring period (range in mean concentrations was 11.0–49.9 mg/L). High losses of inorganic N were driven mainly by high drainage volumes but also, at times, moderate to high concentrations of nitrate-N in drainage water. A histogram of nitrate-N concentrations in drainage is provided in Appendix 3b.

Total P losses were estimated at 0.60 kg/ha for the period 1 September 2014 to 28 February 2018 with respective Year 1, Year 2, Year 3 and current Year 4 period losses totalling 0.06, 0.17, 0.27 and 0.10 kg P/ha (Figure 23c). These losses are low, reflecting primarily low concentrations of total P in drainage water (total P and DRP concentrations averaged 0.03 and 0.02 mg/L respectively). A histogram of total P concentrations in drainage is provided in Appendix 4b.

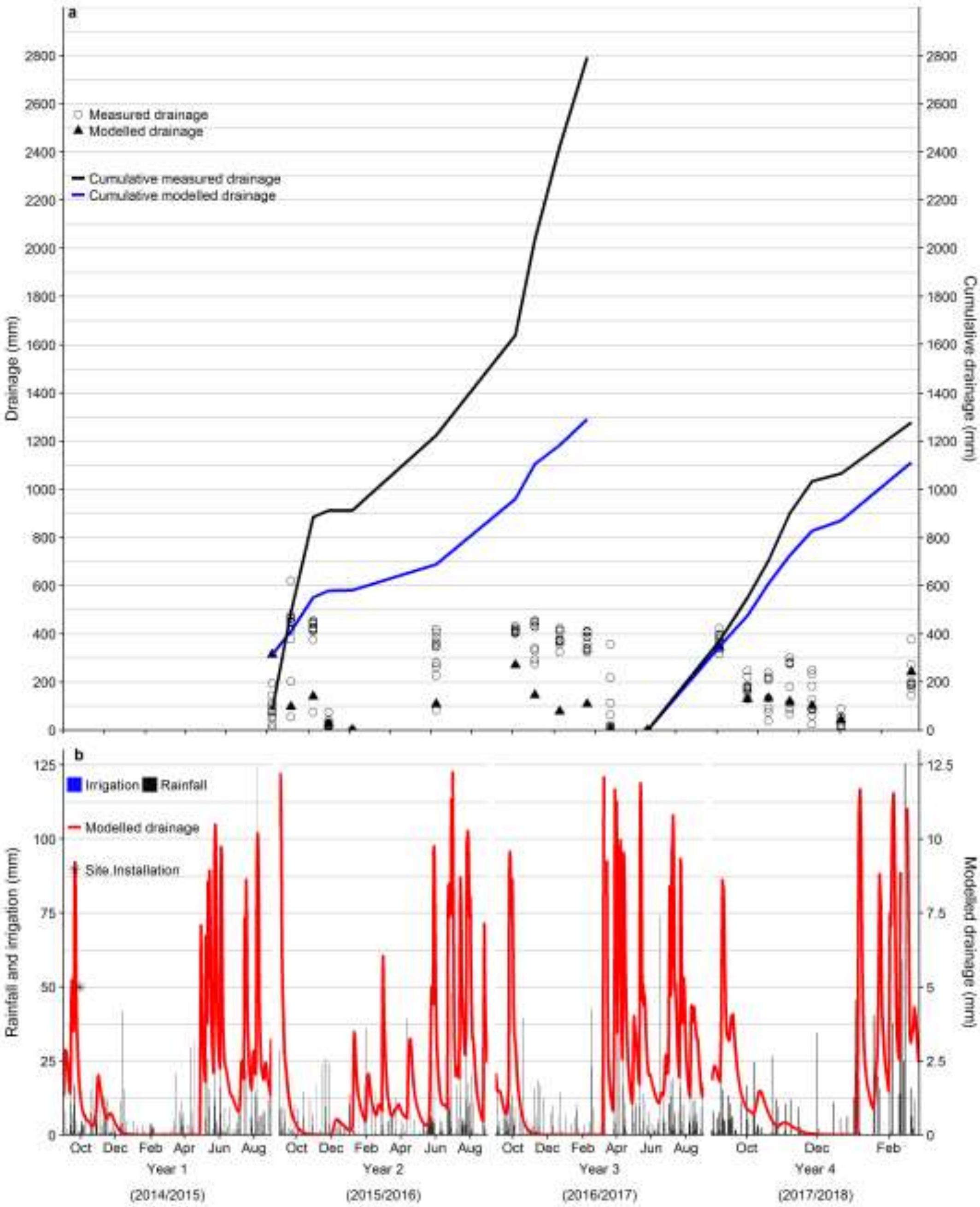

Figure 22. Comparison of measured and modelled drainage data (including drainage volumes for each of the 12 individual fluxmeter units) (a) in conjunction with rainfall and irrigation inputs and modelled drainage at 100 cm (b) at Site 11, Pukekohe for the Year 1 (1 September 2014 to 30 August 2015), Year 2 (1 September 2015 to 30 August 2016), Year 3 (1 September 2016 to 30 August 2017) and current Year 4 (1 September 2017 to 28 February 2018) reporting periods. Modelled data were generated using the mechanistic Soil-Plant-Atmospheric-Model (SPASMO). Cumulative drainage totals have been separated to reflect sustained periods where flooding of all fluxmeters occurred (August 2015 to November 2016) and periods where captured volumes were more closely aligned with modelled data (January 2017 to February 2018).

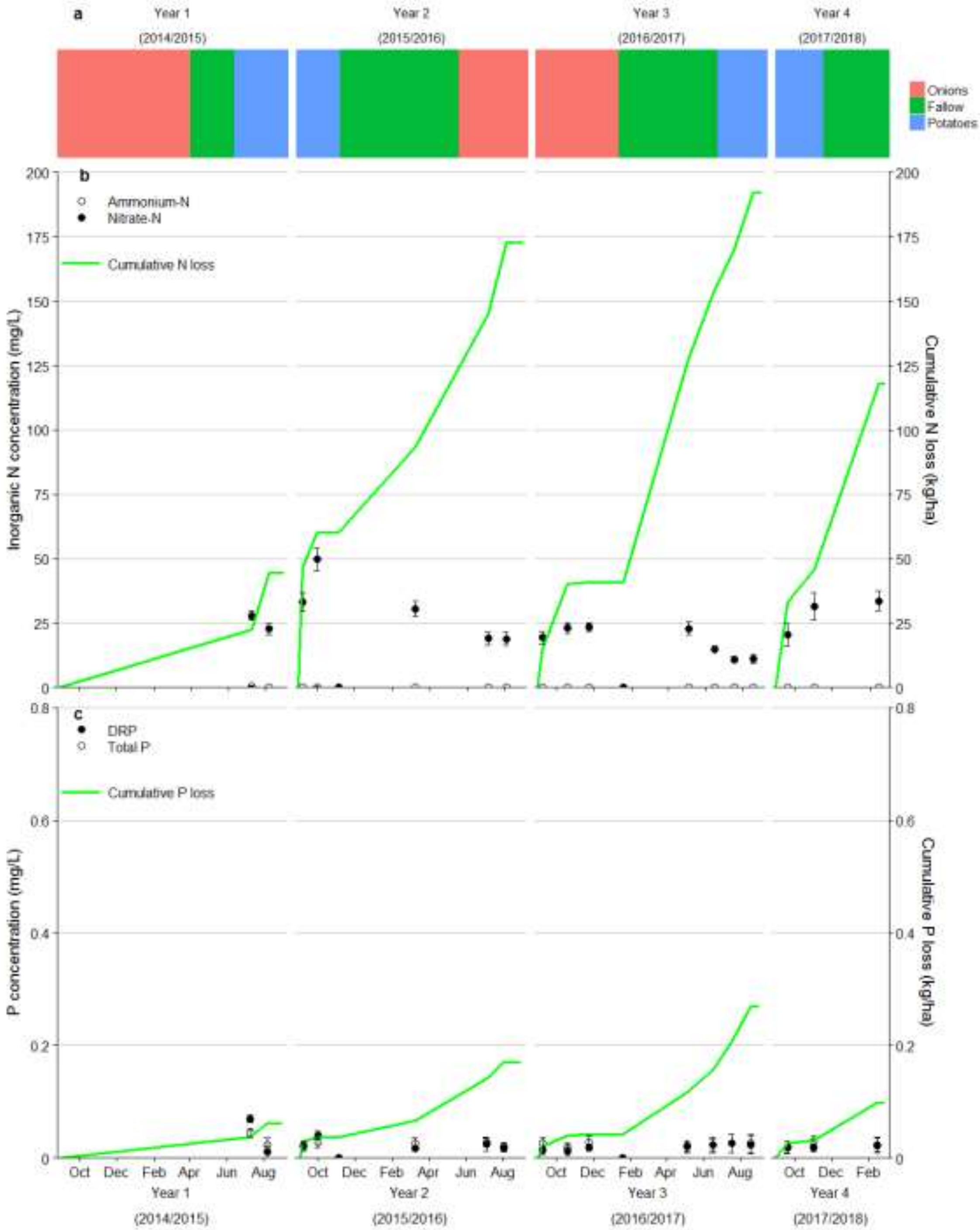

Figure 23. Sequence of crops (a), nitrate and ammonium concentrations and cumulative inorganic nitrogen (N) loss in drainage (b) and total phosphorus (P) and dissolved reactive phosphorus (DRP) concentrations and cumulative total P loss in drainage (c) at Site 11, Pukekohe for the Year 1 (1 September 2014 to 30 August 2015), Year 2 (1 September 2015 to 30 August 2016), Year 3 (1 September 2016 to 30 August 2017) and current Year 4 (1 September 2017 to 28 February 2018) reporting periods. Bars around each point represent the standard error of the mean. Year 1, 2 and 3 cumulative totals include sampling events where losses were calculated using modelled drainage data and measured concentrations.

3.12 Site 12

3.12.1 Site Overview

Site 12 is located near Pukekohe on an intensive vegetable cropping enterprise. The soil type is a Patumahoe clay loam (*mottled orthic granular*). Fluxmeters were originally installed at the site in April 2015, however, following extensive flooding of the units the site was reinstalled in June 2016. The replacement site is located in the same field but approximately 150 m further east. Since installation of the new site there have been two crop sequences including a mustard green crop and winter onions (see Figure 25a).

3.12.2 Site performance

Average measured drainage from the site since re-installation (21 months) totalled 2811 mm, 84% higher than the 1531 mm predicted by the soil water balance model (Figure 24a). Up until August 2017, about 14 months after reinstallation of the site, measured volumes compared well to modelled estimates with respective volumes for this period, totalling 1388 and 1345 mm. Thereafter, captured drainage volumes were substantially higher than modelled estimates, totalling 1466 and 207 mm respectively. As at Site 11, which is also located on a Patumahoe clay loam, excessive drainage volumes are likely related to the creation of a ‘plug hole’ effect following installation of the fluxmeters through more compact subsoil. A similar rapid decrease in hydraulic conductivity with depth was also seen at this site (respective Ksat values for the 0–20, 20–40, 40–60, 60–80 and 80–1000 cm depths were 595, 1.0, 1.3, 0.3 and 0.4 mm/hr). Reoccurrence of this issue is disappointing given that considerable effort was undertaken to mitigate preferential flow into the units (for example, the sampling tube trenches were engineered to direct water away from the fluxmeters). Unfortunately, little could be done to avoid disturbance of the soil profile between the bottom of the cultivation zone and the top of the fluxmeters, despite efforts to repack extracted soil as carefully as possible. Encouragingly, evidence from Site 11 suggests that drainage volumes may return to more normal levels after an extended period of settling (20 months at this site). Until this point, nutrient losses will likely have to be estimated using a combination of modelled drainage and measured concentrations (an approach that is common for other sampling methods such as suction cups).

For the most part, both the timing of drainage events and patterns of accumulation were consistent with modelled predictions with drainage occurring at regular intervals through the year (Figure 24a and b). The exceptions were the two most recent drainage collections in January and February 2018 where a total of 668 mm was collected in the fluxmeters compared to less than 1 mm predicted by the model. It is probable that this drainage originated from bypass flow following heavy rainfall events in January and February (212 mm was recorded between 1 December 2017 and 8 February 2018). Encouragingly, all 12 fluxmeters were effective at capturing drainage with cumulative volumes since installation (including flooded units) ranging from 1593 to 3146 mm (median = 2777 mm, CV = 17%; Appendix 2). The range in cumulative totals reflects spatial differences in drainage patterns across the site as affected by soil and crop factors. There were 10 samplings since reinstallation and the average number of samples used to calculate mean drainage volumes was 11.7 (the range was 9–12). Rainfall and irrigation data were collated from offsite sources (Appendix 1) until November 2017 and during periods where logging equipment was removed to allow for management activity. Soil samples for physical and hydraulic characterisation were taken in February 2017 and results of these analyses were used to parameterise the soil water balance model (Appendix 5b).

3.12.3 Nitrogen and phosphorus losses in drainage

Inorganic N losses were estimated at 125 kg/ha for the period between 15 June 2016 (site reinstallation) and 28 February 2018. In line with reporting periods for the other sites, respective Year 3 and current Year 4 period losses totalled 92 and 33 kg N/ha (Figure 25b). **It is important to note that losses for the current Year 4 period have been calculated using modelled drainage data and measured concentrations and consequently these results should be interpreted with caution**. Nitrate-N was the predominant form of inorganic N in captured drainage with concentrations averaging 12.7 mg/L over the monitoring period (range in mean concentrations was 5.4–26.7 mg/L). High losses of inorganic N were driven mainly by high drainage volumes but also, at times, moderate to high concentrations of nitrate-N in drainage water. A histogram of nitrate-N concentrations in drainage is provided in Appendix 3b.

Total P losses were estimated at 1.07 kg/ha for the period between 15 June 2016 and 28 February 2018 with respective Year 3 and current Year 4 period losses totalling 1.03 and 0.04 kg P/ha (Figure 25c). Apart from the first sampling where P concentrations were comparably high (this reflected a soil settling effect following site installation), concentrations of total P and DRP in drainage water remained low averaging 0.04 and 0.03 mg/L respectively. A histogram of total P concentrations in drainage is provided in Appendix 4b.

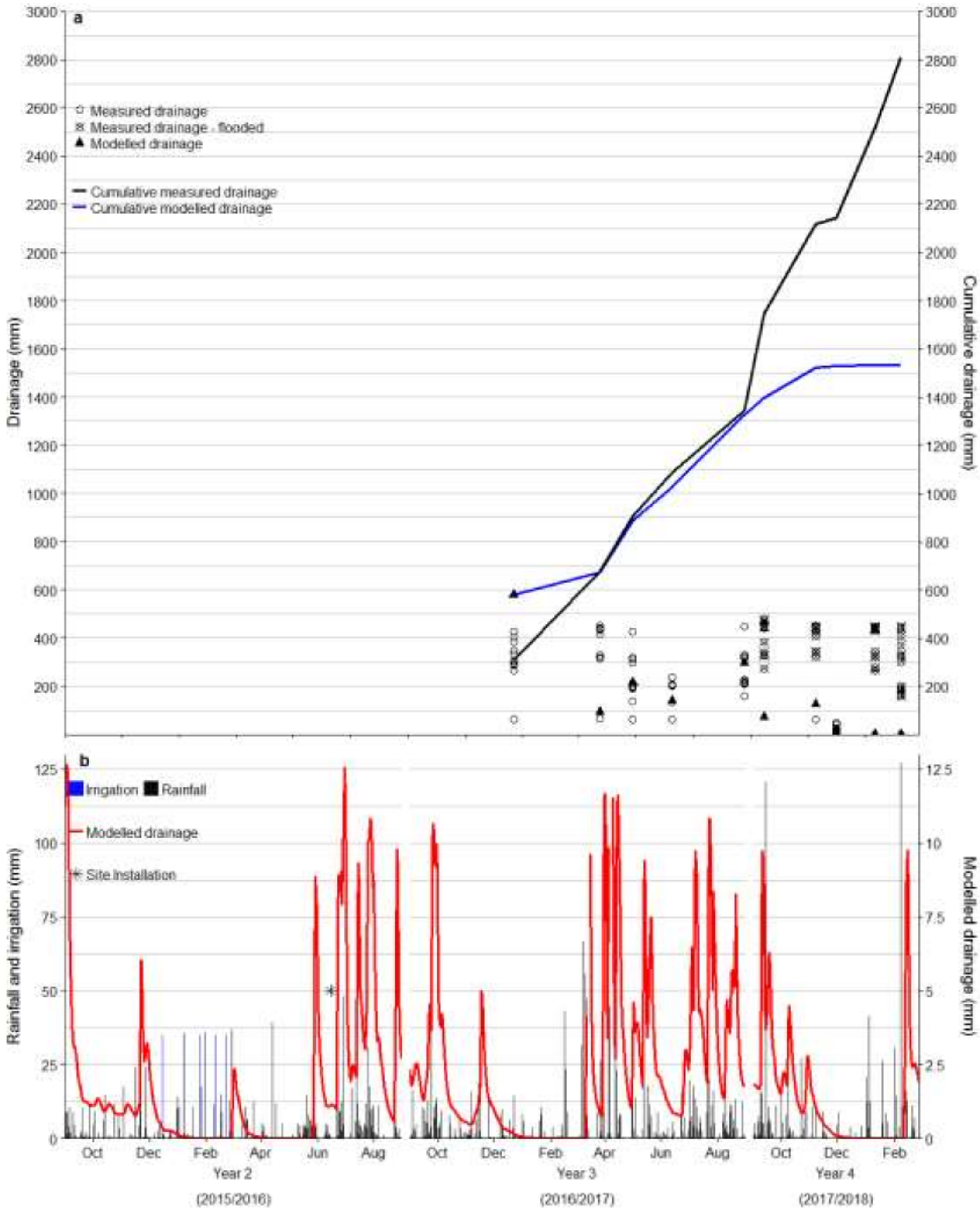

Figure 24. Comparison of measured and modelled drainage data (including drainage volumes for each of the 12 individual fluxmeter units) (a) in conjunction with rainfall and irrigation inputs and modelled drainage at 100 cm (b) at Site 12, Pukekawa for the Year 1 (1 September 2014 to 30 August 2015), Year 2 (1 September 2015 to 30 August 2016), Year 3 (1 September 2016 to 30 August 2017) and current Year 4 (1 September 2017 to 28 February 2018) reporting periods. Modelled data were generated using the mechanistic Soil-Plant-Atmospheric-Model (SPASMO).

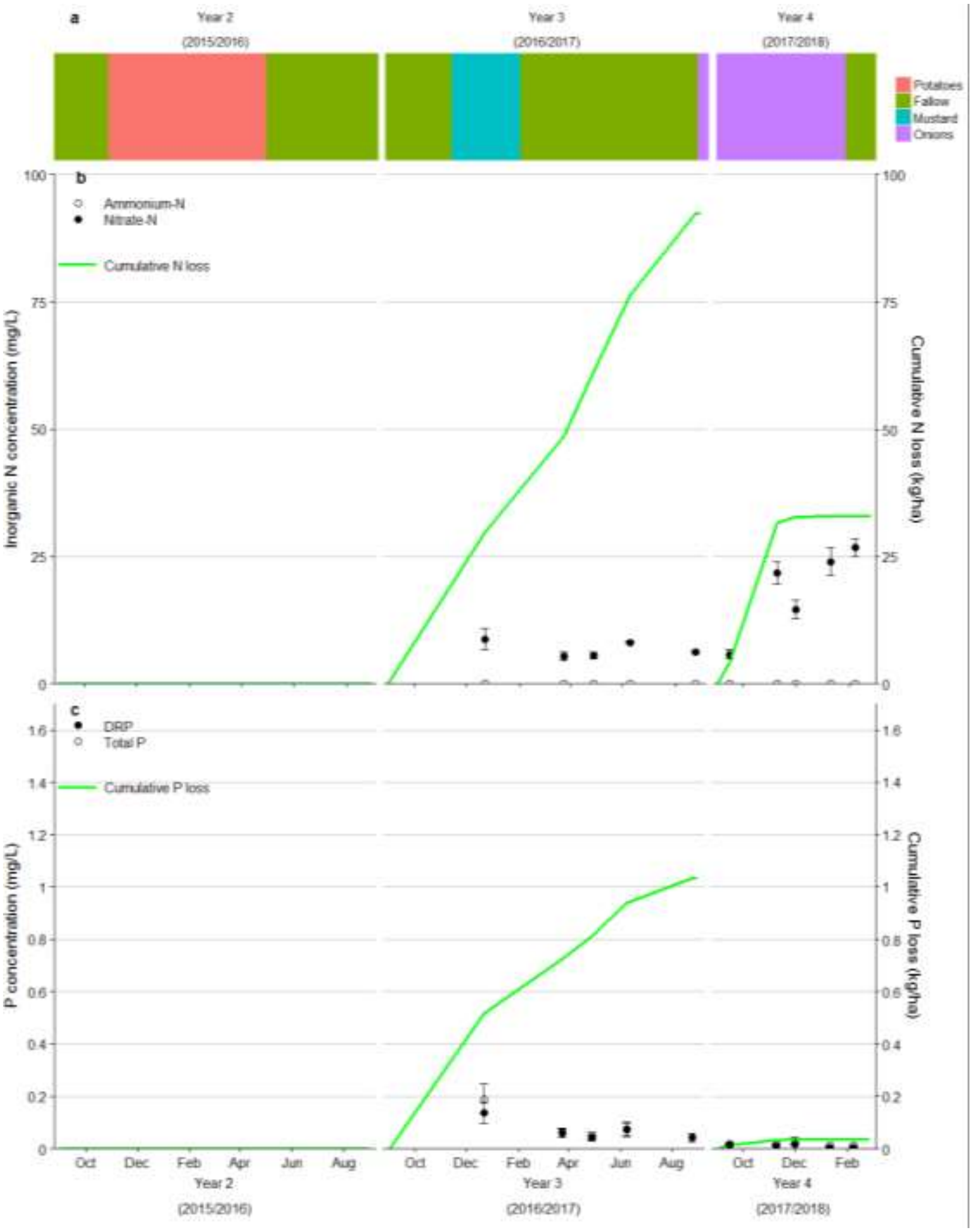

Figure 25. Sequence of crops (a), nitrate and ammonium concentrations and cumulative inorganic nitrogen (N) loss in drainage (b) and total phosphorus (P) and dissolved reactive phosphorus (DRP) concentrations and cumulative total P loss in drainage (c) at Site 12, Pukekawa for the Year 1 (1 September 2014 to 30 August 2015), Year 2 (1 September 2015 to 30 August 2016), Year 3 (1 September 2016 to 30 August 2017) and current Year 4 (1 September 2017 to 28 February 2018) reporting periods. Bars around each point represent the standard error of the mean. Year 4 cumulative totals include sampling events where losses were calculated using modelled drainage data and measured concentrations.

4 ACKNOWLEDGMENTS

The Root Zone Reality project (401484) (Sites 1 to 9) was a collaborative initiative between the Ministry for Primary Industries (Sustainable Farming Fund), the Foundation for Arable Research, Horticulture New Zealand, Environment Canterbury, Horizons Regional Council, Hawke's Bay Regional Council, Ravensdown Fertiliser Cooperative and The New Zealand Institute for Plant and Food Research Limited. The Project Manager was Diana Mathers, Foundation for Arable Research. The HortNZ Northern Fluxmeters project (HortNZ RI 1009) (Sites 10 to 12) was a collaborative initiative between Horticulture New Zealand, Auckland Regional Council, Waikato Regional Council and The New Zealand Institute for Plant and Food Research Limited. The Project Manager was Angela Halliday, Horticulture New Zealand. Funding for the Root Zone Reality and HortNZ Northern Fluxmeters projects ended in July and September 2017 respectively. Subsequent funding for maintenance of the network and sample analysis for the period ending 28 February 2018 was provided by the Foundation for Arable Research, The New Zealand Institute for Plant and Food Research Limited and Ravensdown Fertiliser Cooperative.

We thank our grower collaborators for their support and interest in the project, and for providing information about their farming systems and crop management practices.

We are grateful to Matthew Taylor (Waikato Regional Council) for assistance with soil profile evaluation at Site 12.

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APPENDIX 1. TABLE OF CLIMATE DATA SOURCES FOR THE 12 FLUXMETER SITES SHOWING STATION PROXIMITY TO SITE AND AVAILABLE DATA

Site	Region	Station name	Service provider [1]	Agent number	Distance from site (km)	Rad [2]	Tmean [3]	Tmax [4]	Tmin [5]	VapPress [6]	Wind Run [7]	Rain [8]	Pmsl [9]
1	Canterbury	Methven, Three Springs Cws	NIWA	37920	1.5	x	x	x	x		x	x	x
1	Canterbury	Methven Cws	NIWA	36645	5.2	x	x	x	x		x	x	x
1	Canterbury	Winchmore Ews	NIWA	4764	20.1	x	x	x	x	x	x	x	x
2	Canterbury	Lyndhurst Limwood Farm	NIWA	4740	10.5							x	
2	Canterbury	Methven Cws	NIWA	36645	13.1	x	x	x	x		x	x	x
2	Canterbury	Winchmore Ews	NIWA	4764	16.8	x	x	x	x	x	x	x	x
2	Canterbury	Methven, Three Springs Cws	NIWA	37920	18.6	x	x	x	x		x	x	x
3	Canterbury	Jollies Road	NIWA	4935	2.87							x	
3	Canterbury	Chertsey Cws	NIWA	39661	23	x	x	x	x	x	x	x	x
3	Canterbury	Lincoln, Broadfield Ews	NIWA	17603	29	x	x	x	x	x	x	x	x
3	Canterbury	Ashburton Aero Aws	NIWA	26170	36.1	x	x	x	x		x	x	
4	Manawatu	Levin Aws	NIWA	3275	2.1	x	x	x	x		x	x	x
4	Manawatu	Palmerston North Ews	NIWA	21963	41.8	x	x	x	x	x	x	x	x
5	Manawatu	Bulls, Forest Road	NIWA	17365	5.4							x	
5	Manawatu	Palmerston North Aws	NIWA	21963	33.3	x	x	x	x	x	x	x	x
6	Manawatu	Ohakune Ews	NIWA	31621	5.9							x	
6	Manawatu	Waiouru Airstrip Aws	NIWA	39148	16.3	x	x	x	x	x	x	x	x
7	Hawke's Bay	Te Aute Climate	HBRC		1.1	x	x	x	x			x	
7	Hawke's Bay	Waipawa Ews	NIWA	31620	8	x	x	x	x	x	x	x	x
7	Hawke's Bay	Takapau Plains Aws	NIWA	25820	38.3								
8	Hawke's Bay	Longlands	Hort Plus		1.1		x	x	x			x	
8	Hawke's Bay	Whakatu Ews	NIWA	15876	10.1	x	x	x	x	x	x	x	x
8	Hawke's Bay	Te Aute Climate	HBRC		29.5	x	x	x	x			x	
9	Hawke's Bay	Takapau Plains Aws	NIWA	25820	6.8		x	x	x	x	x	x	x
9	Hawke's Bay	Waipawa Ews	NIWA	31620	25.6	x	x	x	x	x	x	x	x
9	Hawke's Bay	Dannevirke Ews	NIWA	26958	29.5	x	x	x	x	x	x	x	x
10	Waikato	Matamata, Hinuera Ews	NIWA	17030	7		x	x	x	x		x	x
10	Waikato	Tamihana	WRC		10							x	
10	Waikato	Toenepi Ews	NIWA	23908	21.8	x	x	x	x	x	x	x	
10	Waikato	Lake Karapiro Cws	NIWA	37656	24.3	x	x	x	x		x	x	x
11	Auckland	Pukekohe Ews	NIWA	2006	1.9	x	x	x	x	x	x	x	
11	Auckland	Auckland Aero	NIWA	1962	24.6	x	x	x	x	x	x	x	x
12	Auckland	Pukekohe Ews	NIWA	2006	18.6	x	x	x	x	x	x	x	
12	Auckland	Auckland Aero	NIWA	1962	41	x	x	x	x	x	x	x	x

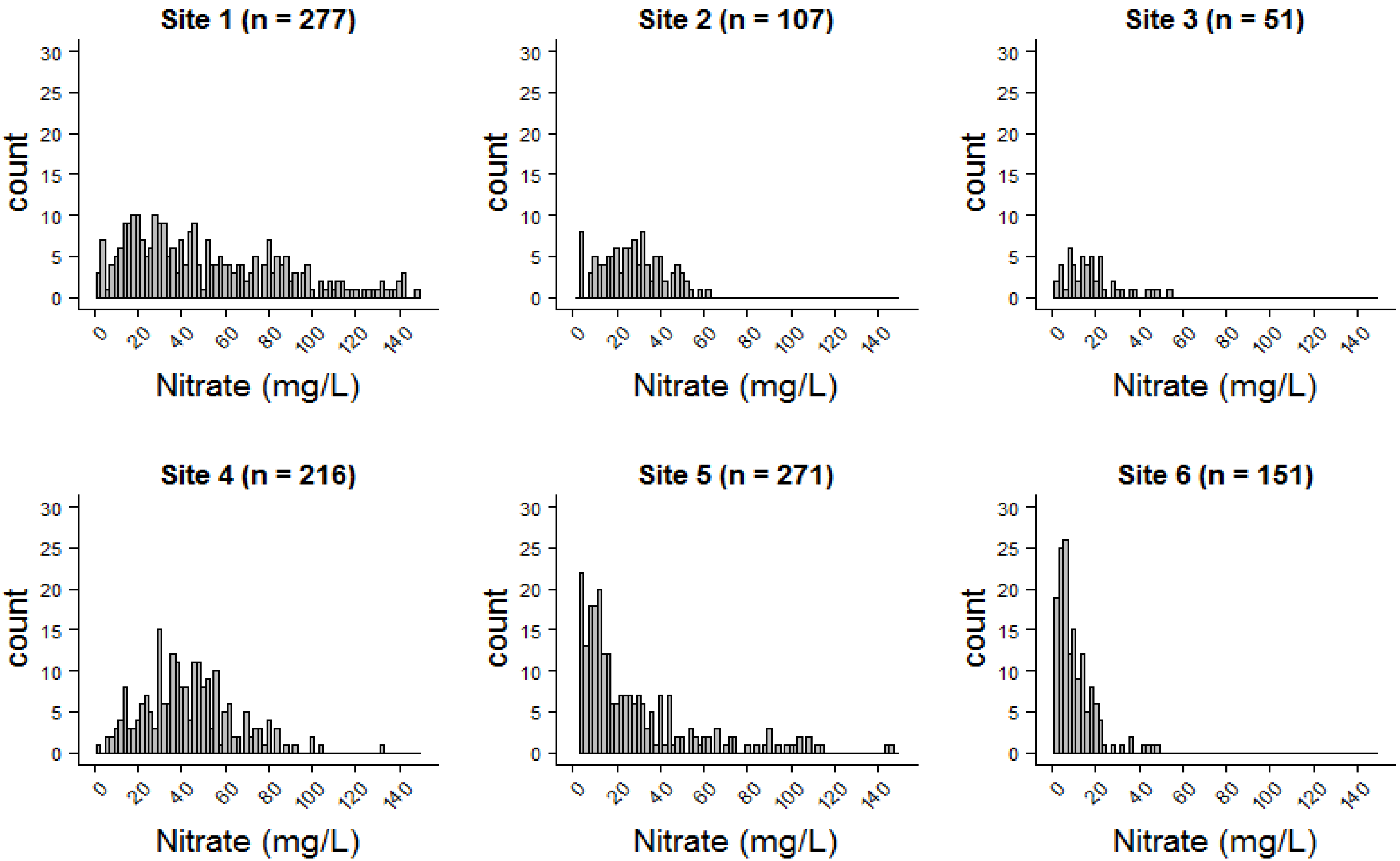
[1] NIWA = National Institute of Water and Atmospheric Research; HBRC = Hawke's Bay Reginal Council. [2] Rad = Daily global radiation (MJ/m^2); [3, 4, 5] Tmean, Tmin, Tmax = Daily mean, minimum and maximum temperature (°C); [6] VapPress = Average daily vapour pressure (hPa); [7] Wind run = Daily average wind run (m/s); [8] Rain = Daily rainfall total (mm); [9] Pmsl = Daily mean sea level pressure (hPa).

APPENDIX 2. CUMULATIVE DRAINAGE TOTALS FOR INDIVIDUAL FLUXMETERS AT EACH OF THE 12 FLUXMETER SITES FOR THE PERIOD BETWEEN SITE INSTALLATION (AUGUST 2014 TO JUNE 2016) AND 28 FEBRUARY 2018

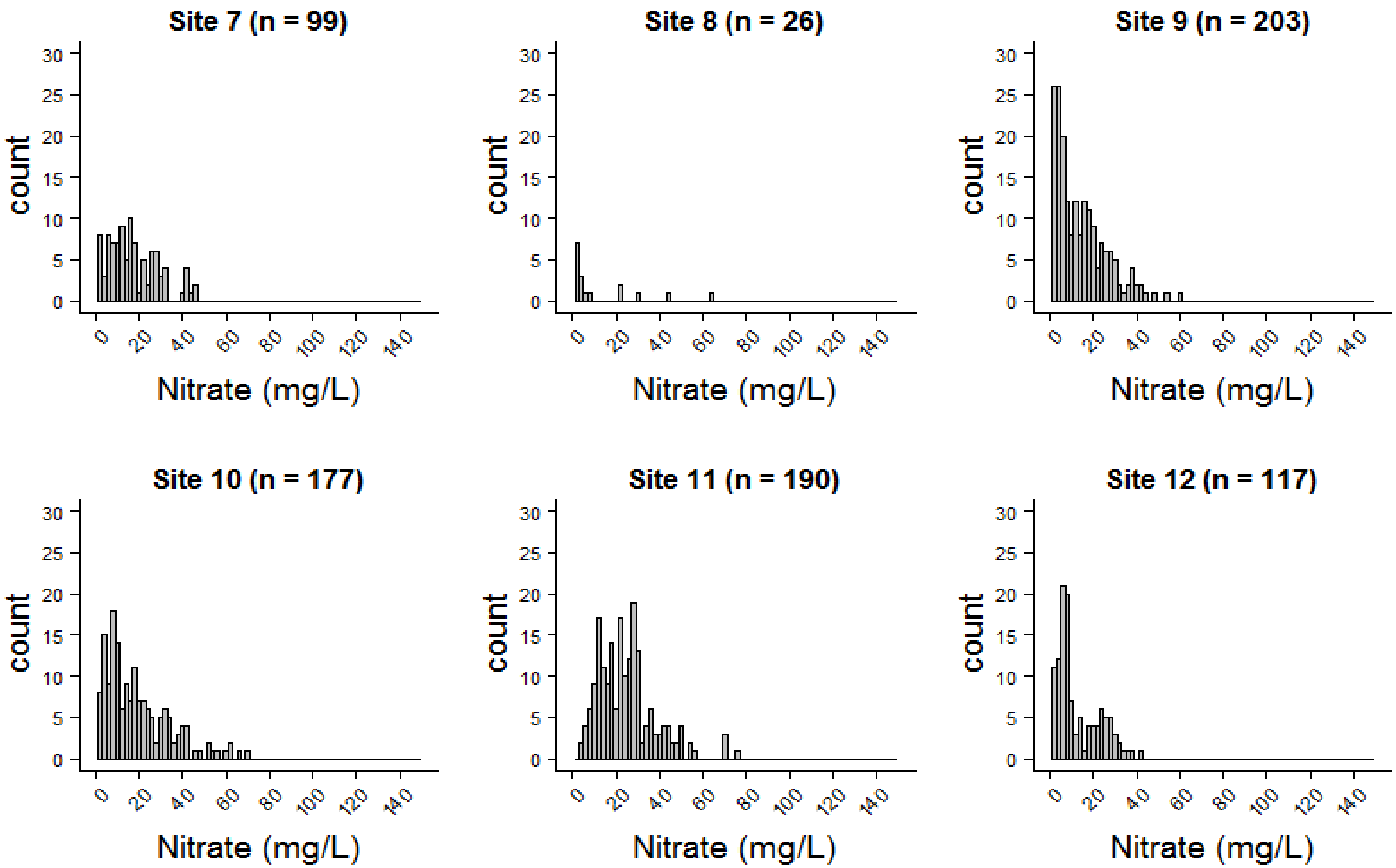
Site	Fluxmeter												n [1]	Mean	Median	Std [2]	CV [3]
	1	2	3	4	5	6	7	8	9	10	11	12					
1	972	470	297	215	217	1125	333	131	1483	638	577	305	30	564	401	431	76
2	124	127	134	141	138	139	189	114	224	500	173	462	27	205	140	136	66
3	352	63	315	313	283	287	274	247	299	250	587	257	27	294	285	134	46
4	322	2183	1611	1429	2069	1195	1695	781	1824	1842	1949	2951	28	1654	1759	792	48
5	922	2950	1024	2640	2800	584	1460	893	2436	1174	3209	3323	29	1951	1948	1120	57
6	586	797	1298	2800	724	3072	181	1272	879	1347	2173	754	18	1324	1076	937	71
7 *	1452	1156	998	1082	1470	1110	1518	1470	1327	1450	1407	1597	30	1336	409	1429	31
8	0	0	236	164	806	1352	635	743	0	7	0	0	20	329	84	439	134
9	1224	1162	653	2629	850	548	1427	1442	432	518	739	205	34	986	795	680	69
10 **	1504	2005	960	1233	424	575	1006	865	-	364	-	514	23	945	523	913	55
11 ***	1247	1409	866	1539	1423	1567	1271	965	930	1447	1382	1292	8	1278	1337	237	19
12 ***	2780	1593	2879	3106	2377	2773	3137	2736	3747	2564	2900	3146	10	2709	2777	465	17

[1] n = number of collection events including occasions where no drainage was recorded. [2] Std = standard deviation. [3] CV = coefficient of variation.
* Includes data for flooding events which occurred in June, July and October 2017.
** Units 9 and 11 stopped working in March 2016. Summary excludes data from these units.
*** Data presented is for the period 18 January 2017 to 28 February 2018, post issues with flooding of the units.
*** Data presented includes flooding events.

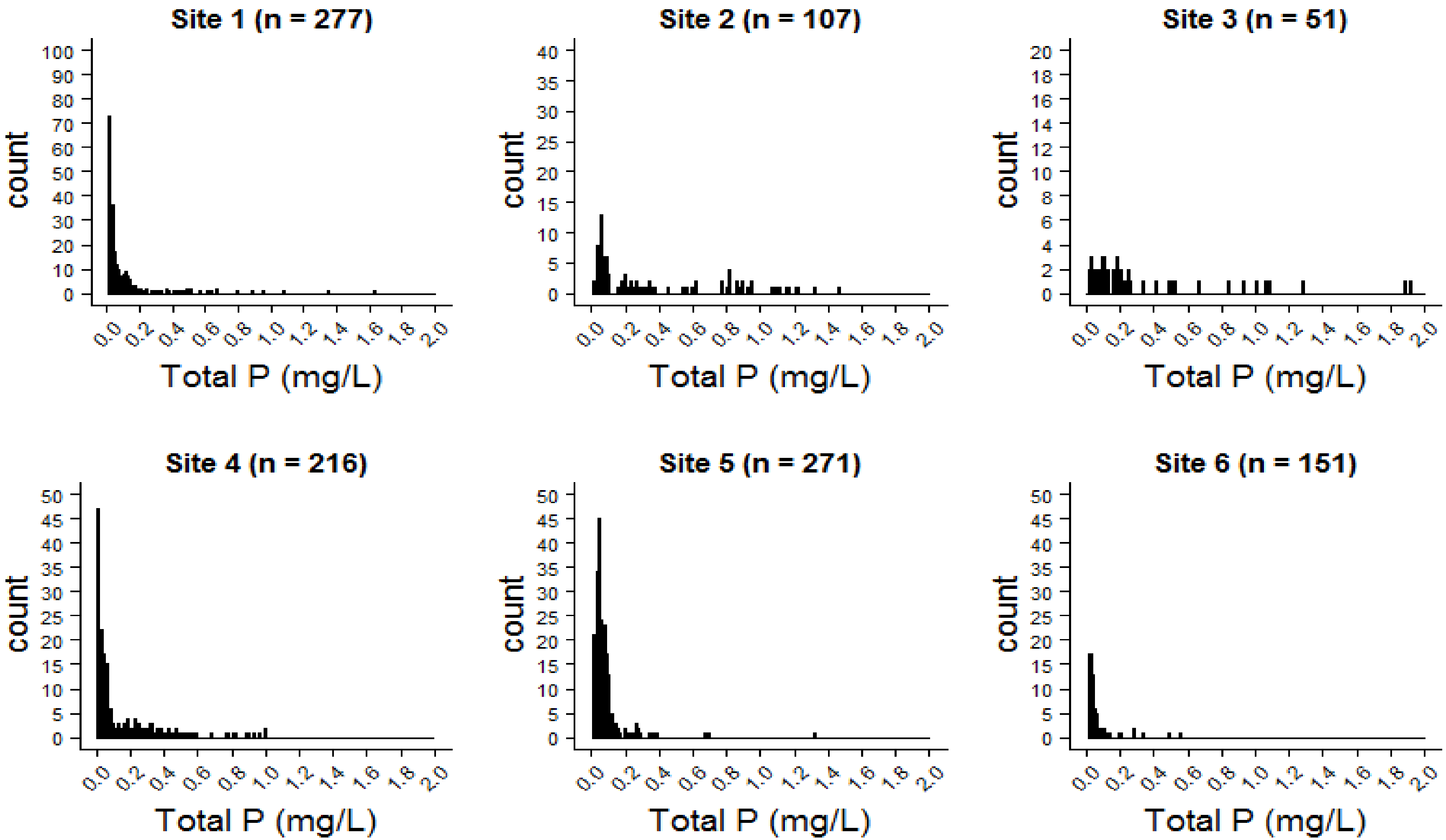
APPENDIX 3A. HISTOGRAM OF NITRATE CONCENTRATIONS IN DRAINAGE WATER FROM SITES 1 TO 6



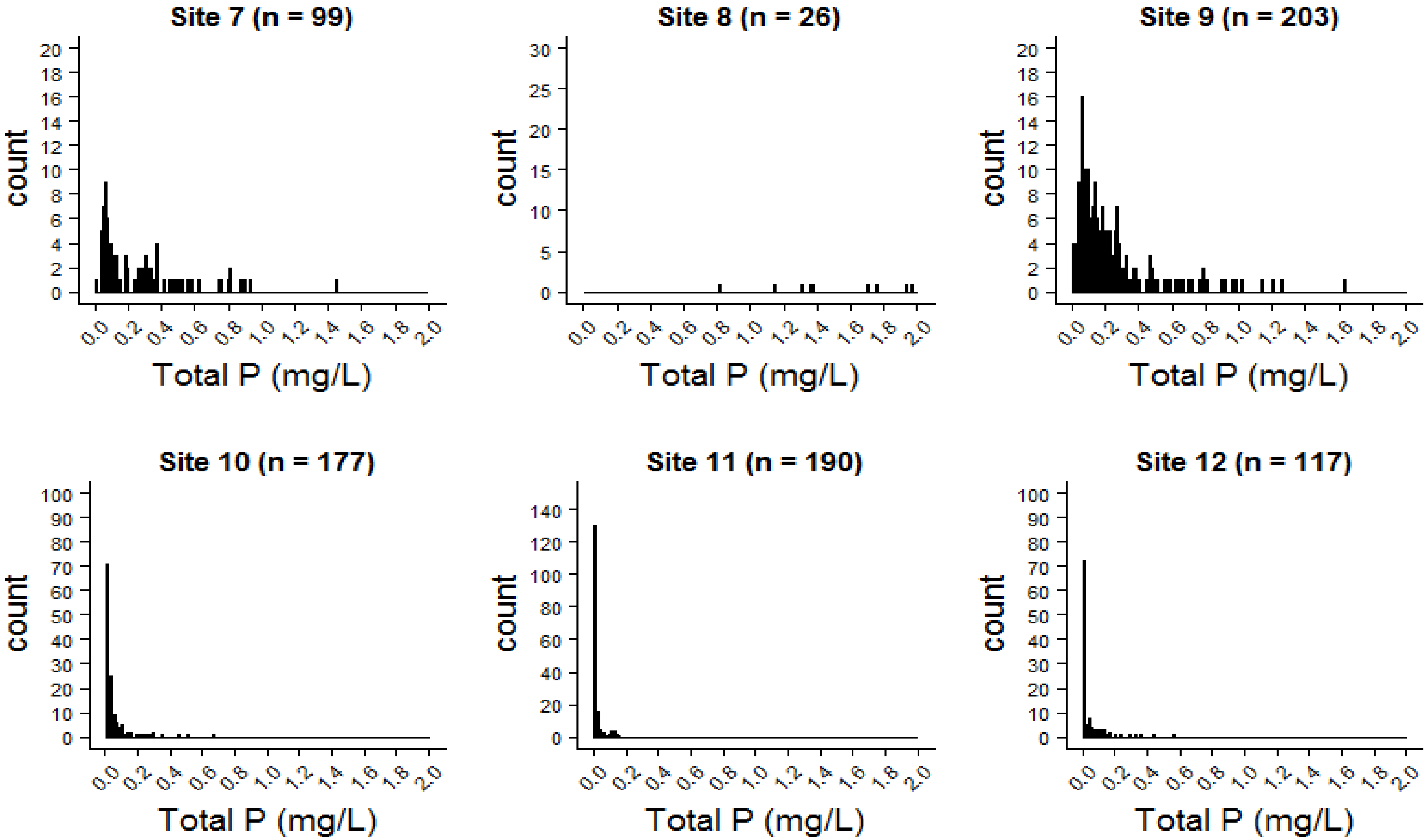
APPENDIX 3B. HISTOGRAM OF NITRATE CONCENTRATIONS IN DRAINAGE WATER FROM SITES 7 TO 12



APPENDIX 4A. HISTOGRAM OF TOTAL PHOSPHORUS (P) CONCENTRATIONS IN DRAINAGE WATER FROM SITES 1 TO 6

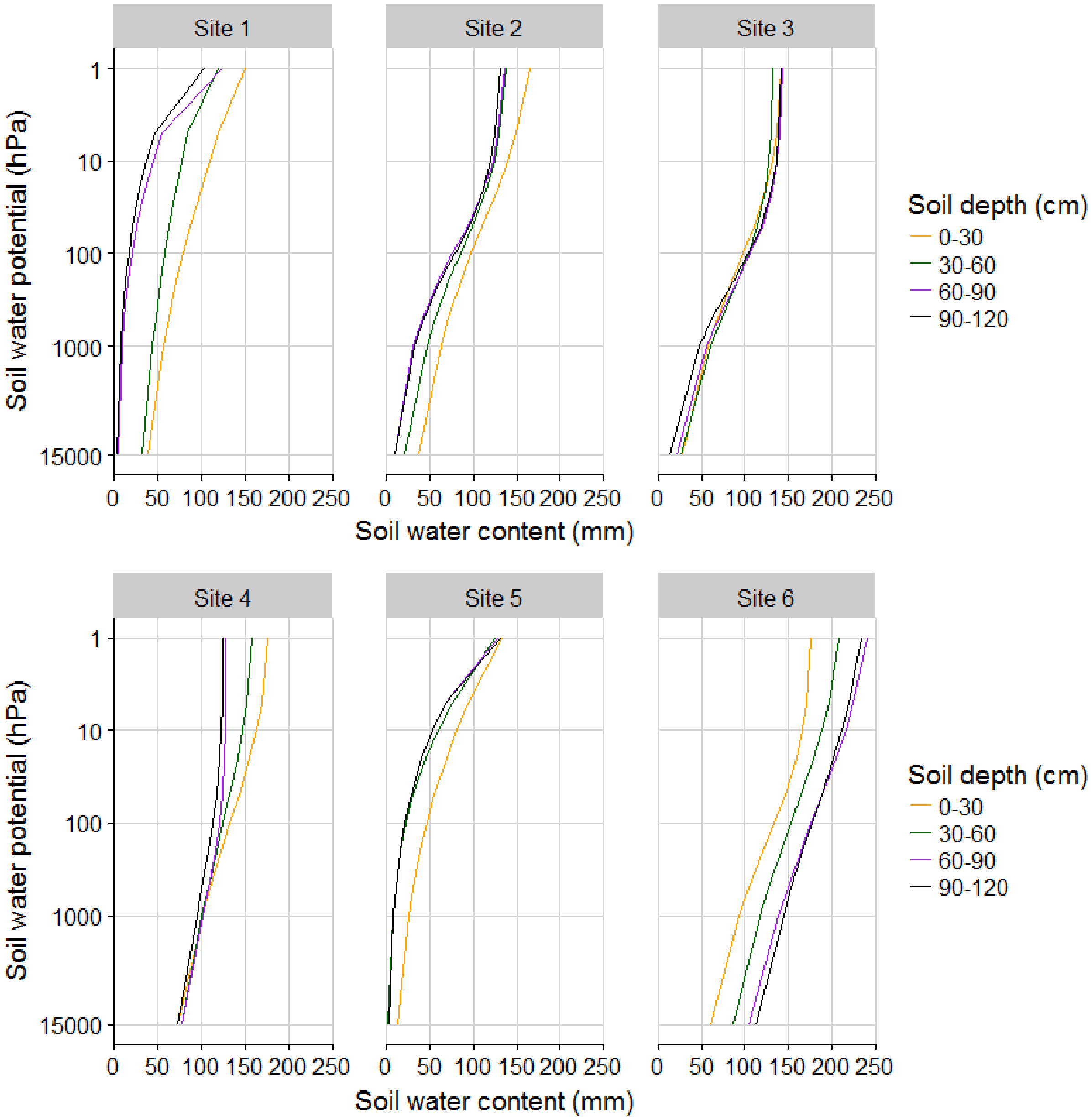


APPENDIX 4B. HISTOGRAM OF TOTAL PHOSPHORUS (P) CONCENTRATIONS IN DRAINAGE WATER FROM SITES 7 TO 12



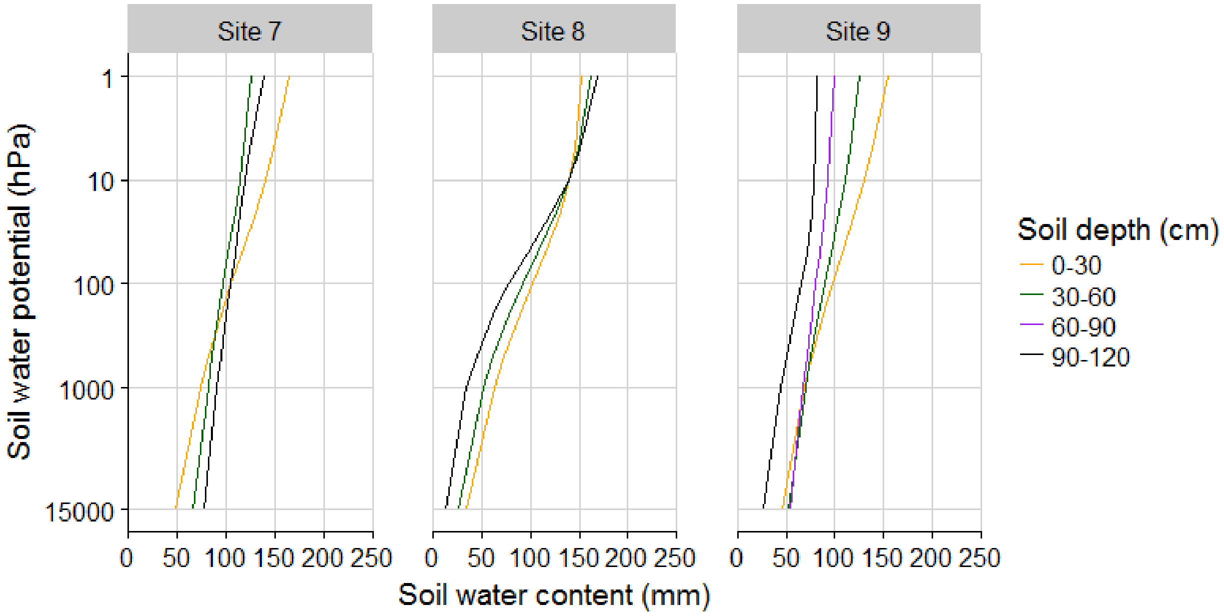
APPENDIX 5A. SOIL WATER RETENTION CURVES FOR SITE'S 1 TO 6

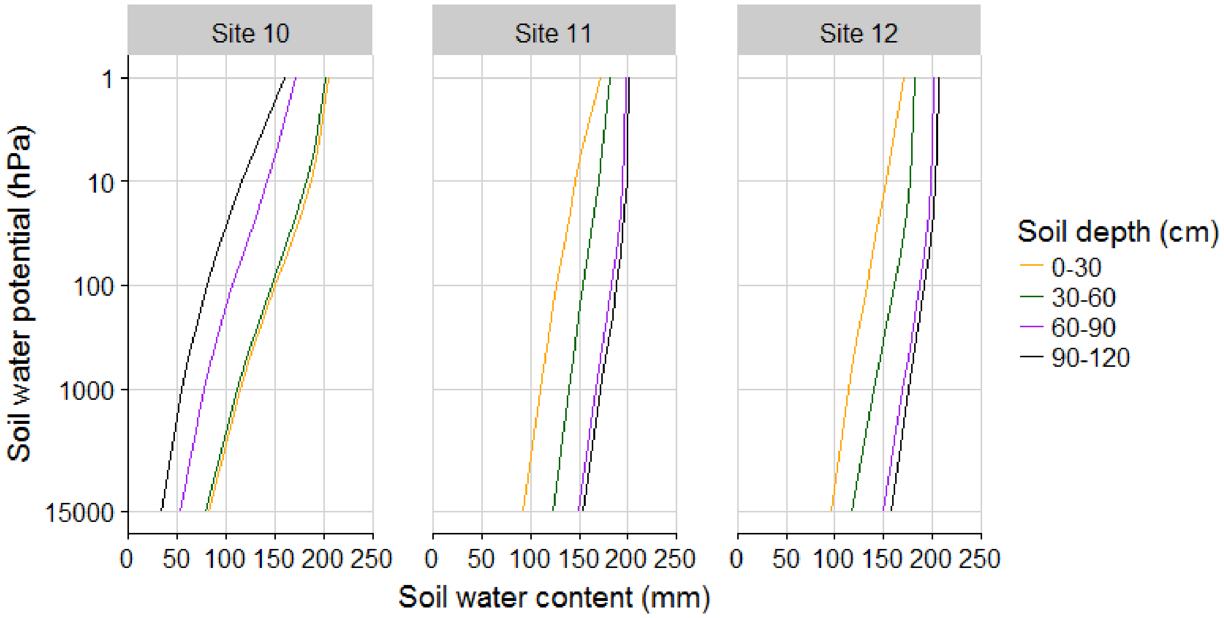
Curves for the 0–30, 30–60, 60–90 and 90–120 cm soil depths were generated using the Van-Genuchten (1980) equation. Soil physical parameters required for curve fitting were obtained from the New Zealand Soils database at Sites 1, 2 and 4 and from onsite soil physical measurements at Sites 3, 5 and 6. Water contents at respective pressure head values of 1, 100, 1000 and 15,000 hPa approximate saturation, field capacity, stress point and permanent wilting point.



APPENDIX 5B. SOIL WATER RETENTION CURVES FOR SITE'S 7 TO 12

Curves for the 0–30, 30–60, 60–90 and 90–120 cm soil depths were generated using the Van-Genuchten (1980) equation. Soil physical parameters required for curve fitting were obtained from the New Zealand Soils database at Sites 7 and 9 from onsite soil physical measurements at Sites 8, 10, 11 and 12. Water contents at respective pressure head values of 1, 100, 1000 and 15,000 hPa approximate saturation, field capacity, stress point and permanent wilting point.





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