CHAPTER 7

NITROGEN MODELLING

The chapter will focus on N modelling as N is the most likely limiting factor for crop production with sludge and most sludge guidelines are based on N. Although P accumulation in N based agricultural sludge application is causing concerns, the complex nature of P in Fe and Al salts treated sludge makes it difficult to model P. In addition, the long term availability of P from sewage sludge treated with Al and Fe salts is still a subject that remains contentious in the scientific literature.

7.1 Model calibration

Field data collected during the 2004/05 growing season was used to determine specific crop parameters of maize, oat and weeping lovegrass in order to calibrate the SWB model. Parameters like specific leaf area, leaf stem partitioning factor, thermal time requirements, maximum root depth, maximum crop height, dry matter water ratio, radiation use efficiency, extinction coefficient, stem to grain translocation, top dry matter at emergence, harvestable dry matter, and maximum grain N concentration were determined from field data. The remaining parameters were obtained from literature.

Selected measured variables, namely total aboveground biomass, grain yield, leaf area index, and aboveground biomass and grain N uptake (Fig. 7. 1) were used to test the success of model calibration. Accuracy of model simulations were assessed based on statistical parameters proposed by De Jager (1994) as presented in Table 7.1.

Table 7.1 Model evaluation statistical parameters with their reliability criteria (after De Jager, 1994)

Statistical parameter abbreviation	Extended meaning of abbreviation	Reliability criteria
r^2	Coefficient of determination	> 0.8
D	Willmott (1982) index of agreement	> 0.8
RMSE	Root mean square error	-
MAE(%)	Mean absolute error expressed as a percentage of the mean of the measured values	< 20

Generally the model was calibrated successfully for maize, oats, and weeping lovegrass. This is because most of the simulated values for the selected variables agreed closely to measured values (Fig. 7.1) and all the statistical parameters were within the ranges prescribed by De Jager et al. (1994) (Table 7.2). Maize aboveground biomass was underestimated towards the end of the season. Nevertheless, the difference was not significant and all the statistical parameters were within the ranges prescribed by De Jager (1994) (Table 7.2). Similarly, maize above ground N uptake was underestimated towards the end of the season, which is understandable considering the underestimation of aboveground biomass. This was also indicated by a high RMSE (52.74 kg N ha^{-1}).

Model simulation results for oats LAI, aboveground biomass, grain yield, aboveground biomass N uptake and grain N uptake were estimated with high accuracy. Similarly, simulated weeping lovegrass hay yield was close to the measured values for the first cut of each year. It was, however, underestimated during the second cut causing the underestimation of hay N uptake during this harvest cycle. Nevertheless, all the variables were estimated within the acceptable ranges of statistical accuracy.

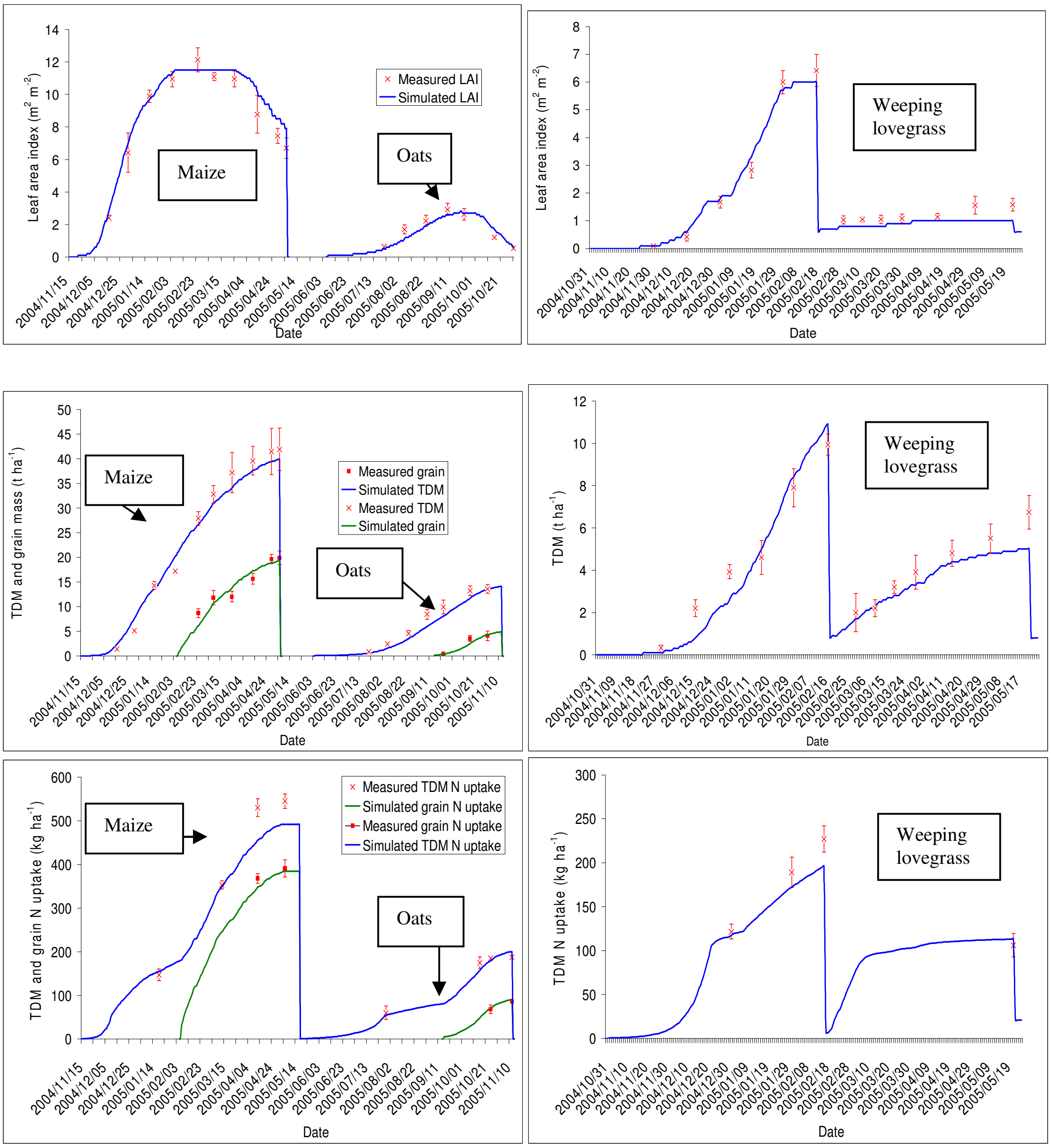

Figure 7.1 Simulated (solid lines) and measure values (symbols with standard deviation) from top to bottom of leaf area index, aboveground biomass (TDM), and aboveground biomass N uptake for the 16 Mg ha^{-1} sludge treatment.

Table 7.2 Statistical parameters of the SWB model calibration simulations for maize, oats, and weeping lovegrass during the 2004/05 growing season.

Variable	n	D	RMSE	MAE (%)	R^2
Maize					
LAI	10	0.94	0.82	7.79	0.98
Aboveground biomass	10	0.98	2.18	7.40	0.99
Aboveground biomass N uptake	4	0.92	52.74	8.47	0.99
Grain	6	0.88	1.72	9.72	0.95
Grain N uptake (combined irrigated maize-oats)†	4	0.99	12.82	3.71	0.99
Oats					
LAI	7	0.92	0.38	17.06	0.93
Aboveground biomass	7	0.92	1.52	15.18	0.99
Aboveground biomass N uptake	4	0.95	13.19	6.73	0.98
Grain	3	0.90	0.77	17.39	0.95
Weeping lovegrass					
LAI	13	0.98	0.34	14.24	0.99
Aboveground biomass	13	0.92	0.89	15.81	0.97
Aboveground biomass N uptake	4	0.87	20.84	9.15	0.99

†Grain N uptake by irrigated maize and oats for the irrigated maize-oat rotation double cropping system was combined for statistical analyses due to few data points measured for oats.

7.2 Model corroboration

Model corroboration was conducted using variables collected from independent data sets during the 2004/05 to 2007/08 growing seasons for maize, oats and weeping lovegrass. The variables used to evaluate the accuracy of the model were LAI, aboveground biomass, grain (agronomic crops), and aboveground biomass and grain N uptake.

7.2.1 Agronomic crops

Generally evaluation of the model against three year combined independent data sets for dryland maize and irrigated maize-oat rotation proved to be very successful. All indicators were simulated for selected treatments, as all the statistical parameters were within the accuracy limits prescribed by De Jager (1994) (Table 7.3).

Simulations for selected treatments and their statistical analyses are presented in Figs. 7.2 to 7.4 and Table 7.3. Although, the model underestimated in some instances and overestimated in others, the statistical parameters for both dryland maize and irrigated maize-oat rotation were within the accuracy limits. There were, however, a few exceptions, such as for the leaf area index (LAI), aboveground biomass (TDM), and grain yield (HDM) of the 8 Mg ha^{-1} yr^{-1} sludge treated dryland maize. The model significantly underestimated LAI and TDM during 2004/05 and 2007/08 growing seasons and HDM during the 2004/05 and 2005/06. This was indicated by a slightly higher MAE (%) value of 29, for the LAI and 20 for both TDM and HDM, compared with the prescribed range of $< 20\%$. Generally the model predicted the indicators more accurately under irrigated maize-oat rotation than dryland maize cropping.

Table 7.3 Statistical parameters of the SWB model corroboration for maize, oats, and weeping lovegrass using combined data collected during the 2004/05 to 2007/08 growing seasons.

Variables	n	D	RMSE	MAE (%)	R^2
Dryland maize 8 Mg ha^{-1} per annum sludge treatment					
LAI	11	0.80	0.38	29	0.98
Aboveground biomass	16	0.87	2.37	20	0.99
Aboveground biomass N uptake	9	0.85	31.00	17	0.93
Grain	10	0.87	1.10	20	0.91
Grain N uptake	6	0.88	17.00	14	0.99
Irrigated maize-oat rotation 8 Mg ha^{-1} per annum sludge treatment					
LAI	25	0.82	1.00	12.22	0.98
Aboveground biomass	26	0.97	2.55	10.68	0.99
Aboveground biomass N uptake	17	0.92	44.01	14.00	0.96
Grain	17	0.95	1.17	7.00	0.98
Grain N uptake	10	0.89	41.26	14.00	0.95
Irrigated maize-oat rotation 16 Mg ha^{-1} per annum sludge treatment					
LAI	23	0.94	0.71	18	0.96
Aboveground biomass	29	0.94	2.69	15	0.97
Aboveground biomass N uptake	15	0.89	43.00	15	0.97
Grain	18	0.92	1.59	16	0.97
Grain N uptake	10	0.90	31.71	15	0.97

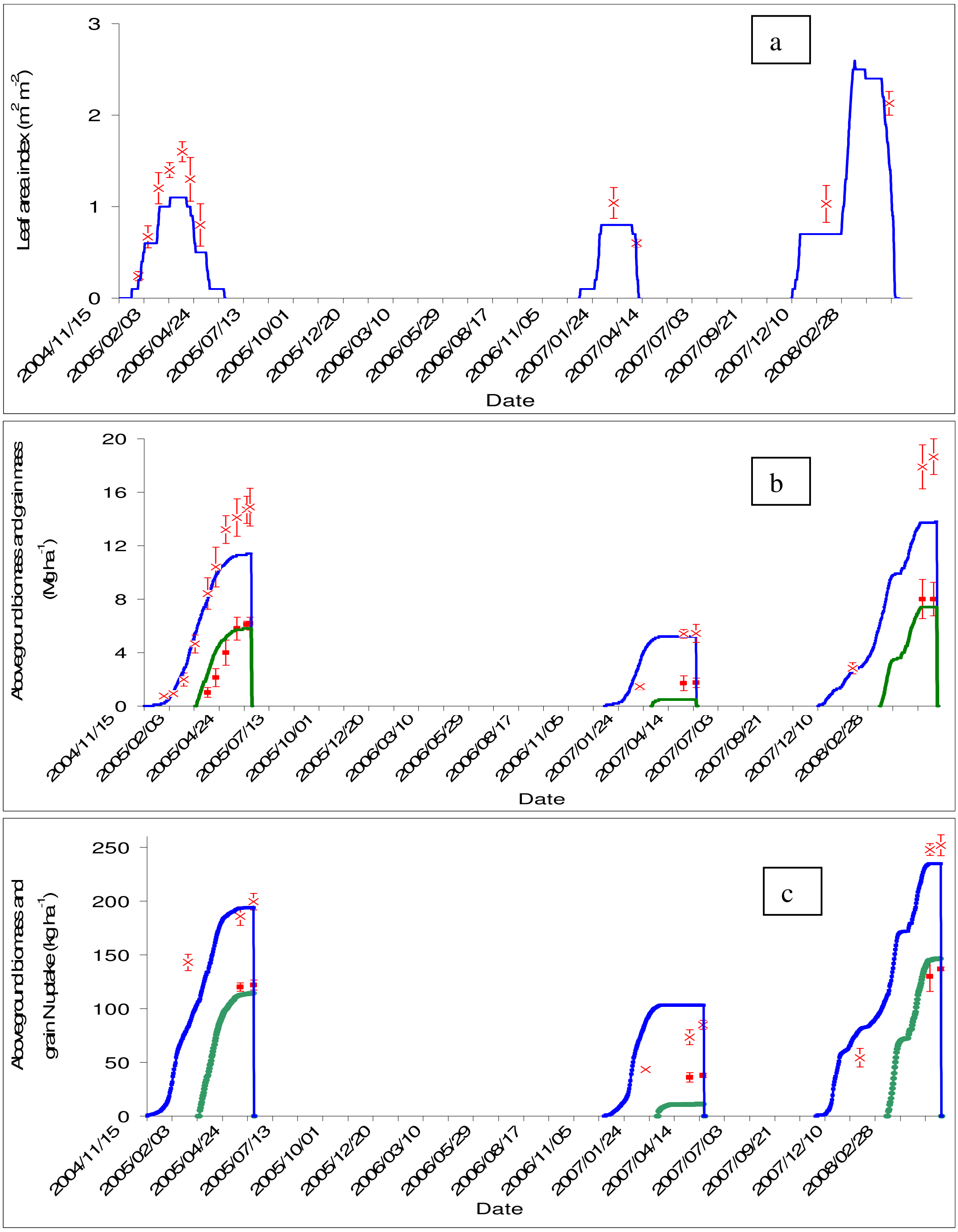

Figure 7.2 Simulated (solid lines) and measure values (symbols) of leaf area index (a), aboveground biomass (TDM), and aboveground biomass N uptake (c) for the 8 Mg ha^{-1} per annum sludge treated dryland maize during the 2004/05 to 2007/08 study period.

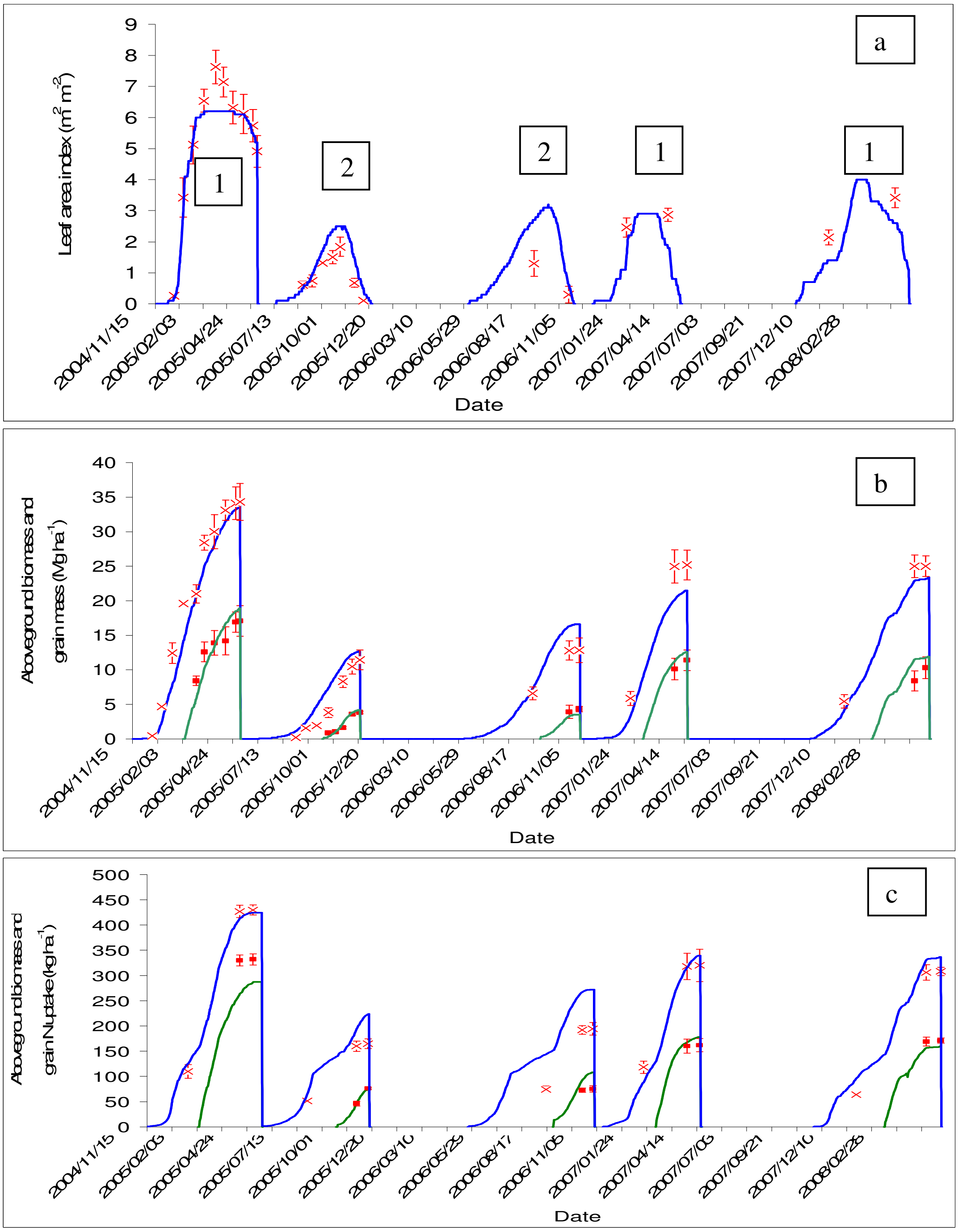

Figure 7.3 Simulated (solid lines) and measure values (symbols) of leaf area index (a), aboveground biomass (TDM), and aboveground biomass N uptake (c) for the 8 Mg ha^{-1} per annum sludge treated irrigated maize(1)-oat(2) rotation during the 2004/05 to 2007/08 study period.

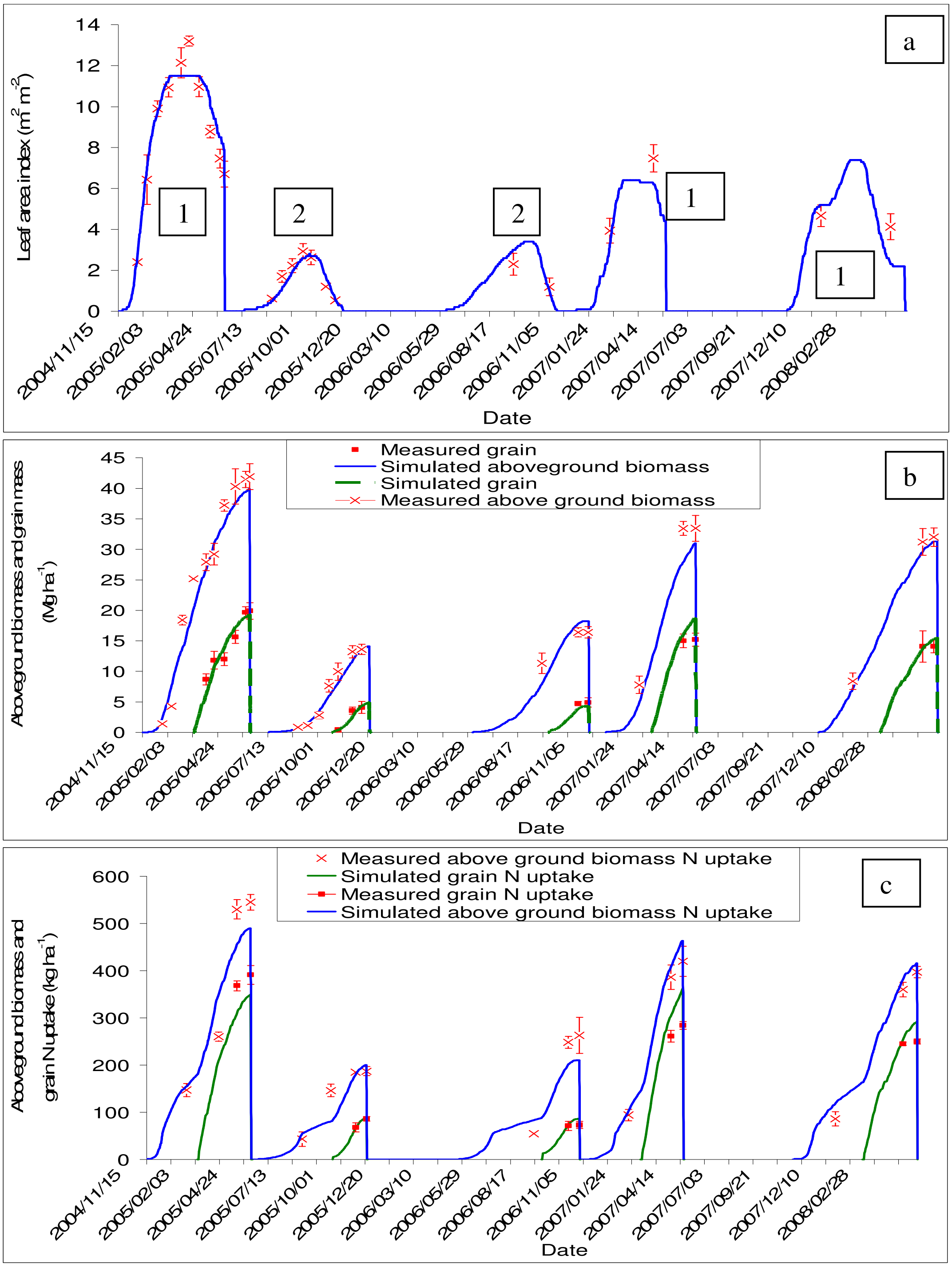

Figure 7.4 Simulated (solid lines) and measure values (symbols) of leaf area index (a), aboveground biomass (TDM), and aboveground biomass N uptake (c) for the 16 Mg ha^{-1} per annum sludge treated irrigated maize(1)-oat(2) rotation during the 2004/05 to 2007/08 study period.

7.2.2 Weeping lovegrass

During model corroboration of weeping lovegrass using four year combined data of all treatments, prediction of LAI, aboveground biomass, and aboveground biomass N uptake had poor agreement with the measured values. All the statistical parameters for the above mentioned variables were not within the prescribed ranges. Updating soil water content after every hay cut using field measurements, however, improved model performance (Table 7.4).

Table 7.4 Statistical parameters of the SWB model corroboration for weeping lovegrass without and with updating soil water content after every hay cut using combined data collected during the 2004/05 to 2007/08 growing seasons.

Variables	n	D	RMSE	MAE (%)	R^2
Weeping lovegrass					
Without updating soil water content					
LAI	102	0.74	0.83	38	0.85
Aboveground biomass	102	0.51	1.97	37	0.74
Aboveground biomass N uptake	30	0.36	35.00	24	0.64
Soil water content updated after every hay cut					
LAI	102	0.92	0.43	22	0.95
Aboveground biomass	102	0.84	1.13	22	0.91
Aboveground biomass N uptake	30	0.49	32.00	21	0.71

Individual simulations, without updating soil water content, (Figs. 7.5 to 7.7) and after updating soil water content (Figs. 7.8 to 7.10) were also conducted for selected treatments, namely for the control, 8, and 16 Mg ha^{-1} sludge treatments. The statistical analyses for these simulations are presented in Appendix (Table A3). For scenarios, where the soil water content was updated after every hay cut, the model simulated the correct trend and magnitude for LAI, thereby showing good predictability under various N supply conditions varying from zero added N to far more than the crop demand. Although the model underestimated LAI in most cases, the statistical parameters were within the prescribed limits. The simulated LAI for all the treatments was predicted with a RMSE of 0.44-0.47 m^2 leaf area m^{-2} ground area.

During model corroboration runs of scenarios where the soil water content was updated after every hay cut, predictions of weeping lovegrass aboveground biomass for the control, 8, and 16 Mg ha^{-1} sludge treatments were underestimated in most cases during the study period. The statistical parameters for the 8 and 16 Mg ha^{-1} sludge treatments were within the prescribed ranges. The control treatment, however, had lower coefficient of determination (0.71) than the prescribed (>0.8).

Aboveground biomass N uptake model prediction during model corroboration was poor for all treatments, because the statistical parameters were not within the prescribed ranges (Table 7.4). Generally, the poor model performance for perennial dryland pasture (weeping lovegrass) was because the model does not simulate long-term perennial grass growth mechanistically. The model does not have a mechanistic way of simulating the dormancy during winter and re-growth in spring for perennial grass. Therefore, the model needs to be improved.

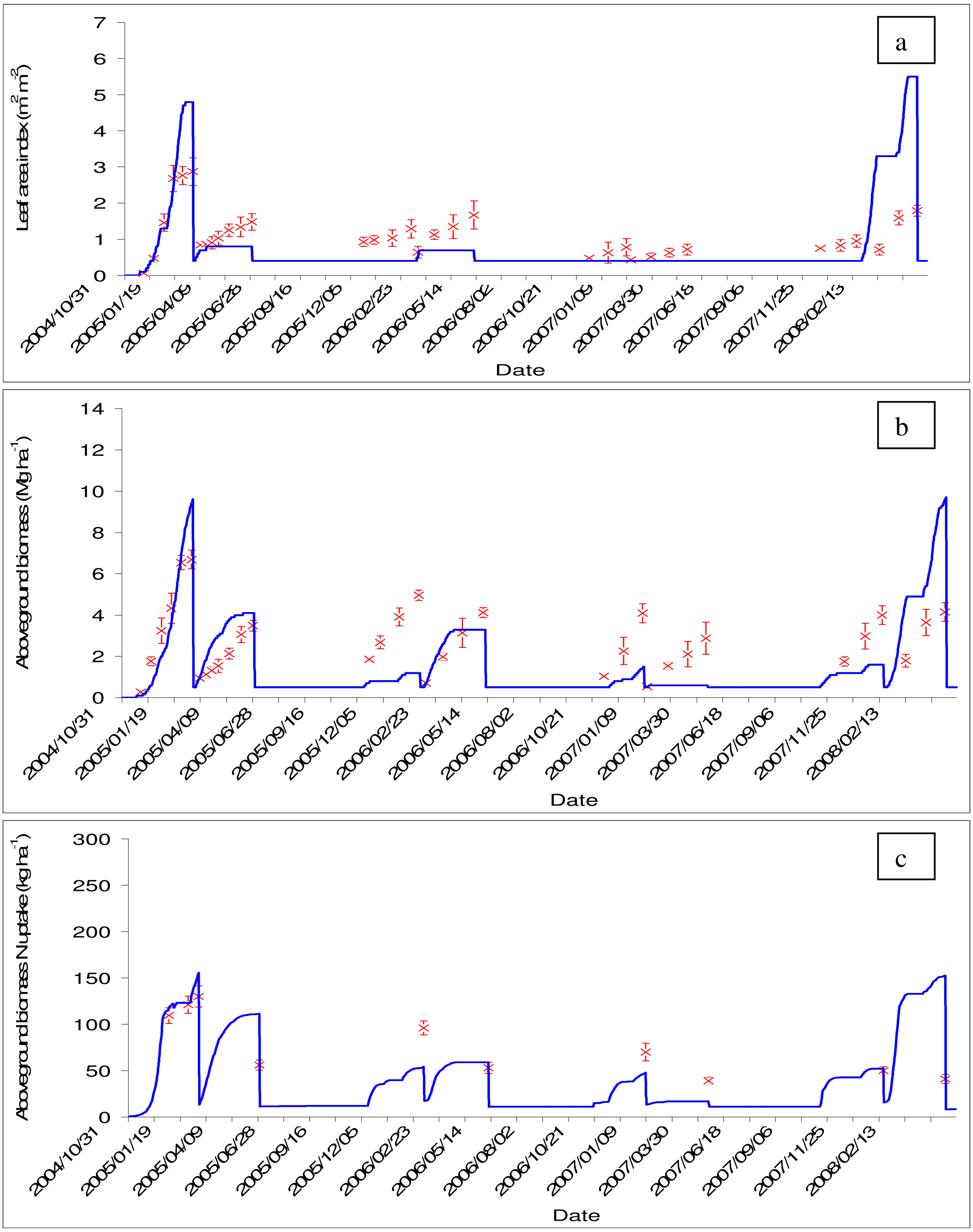

Figure 7.5 Simulated (solid lines) and measured values (symbols with standard deviation) of weeping lovegrass leaf area index (a), aboveground biomass (b), and aboveground biomass N uptake (c) for the control treatment (0 nutrients applied) during the 2004/05 to 2007/08 study period (without updating soil water).

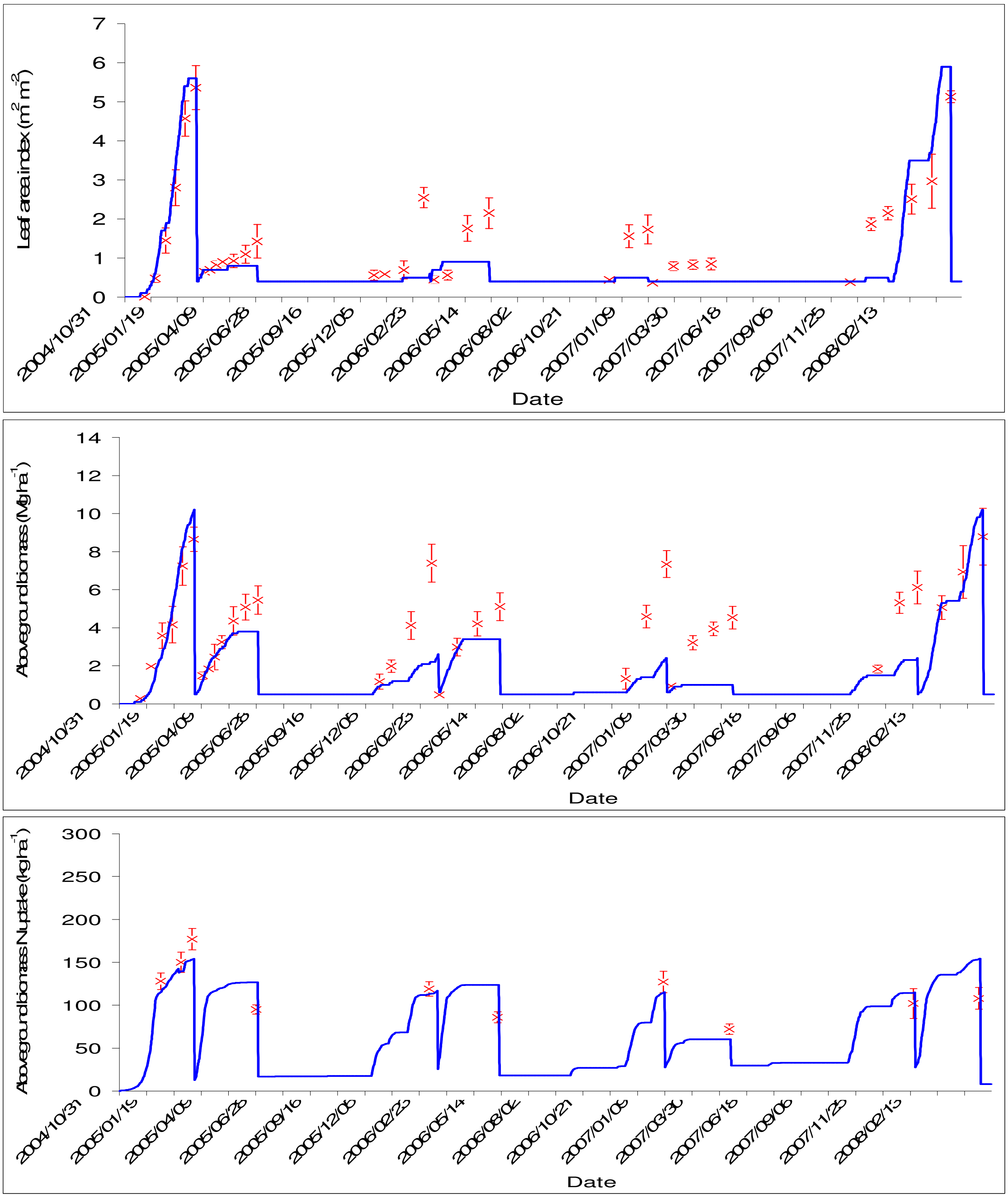

Figure 7.6 Simulated (solid lines) and measured values (symbols with standard deviation) of weeping lovegrass leaf area index (a), aboveground biomass (b), and aboveground biomass N uptake (c) for the 8 Mg ha^{-1} yr^{-1} sludge treatment during the 2004/05 to 2007/08 study period (without updating soil water).

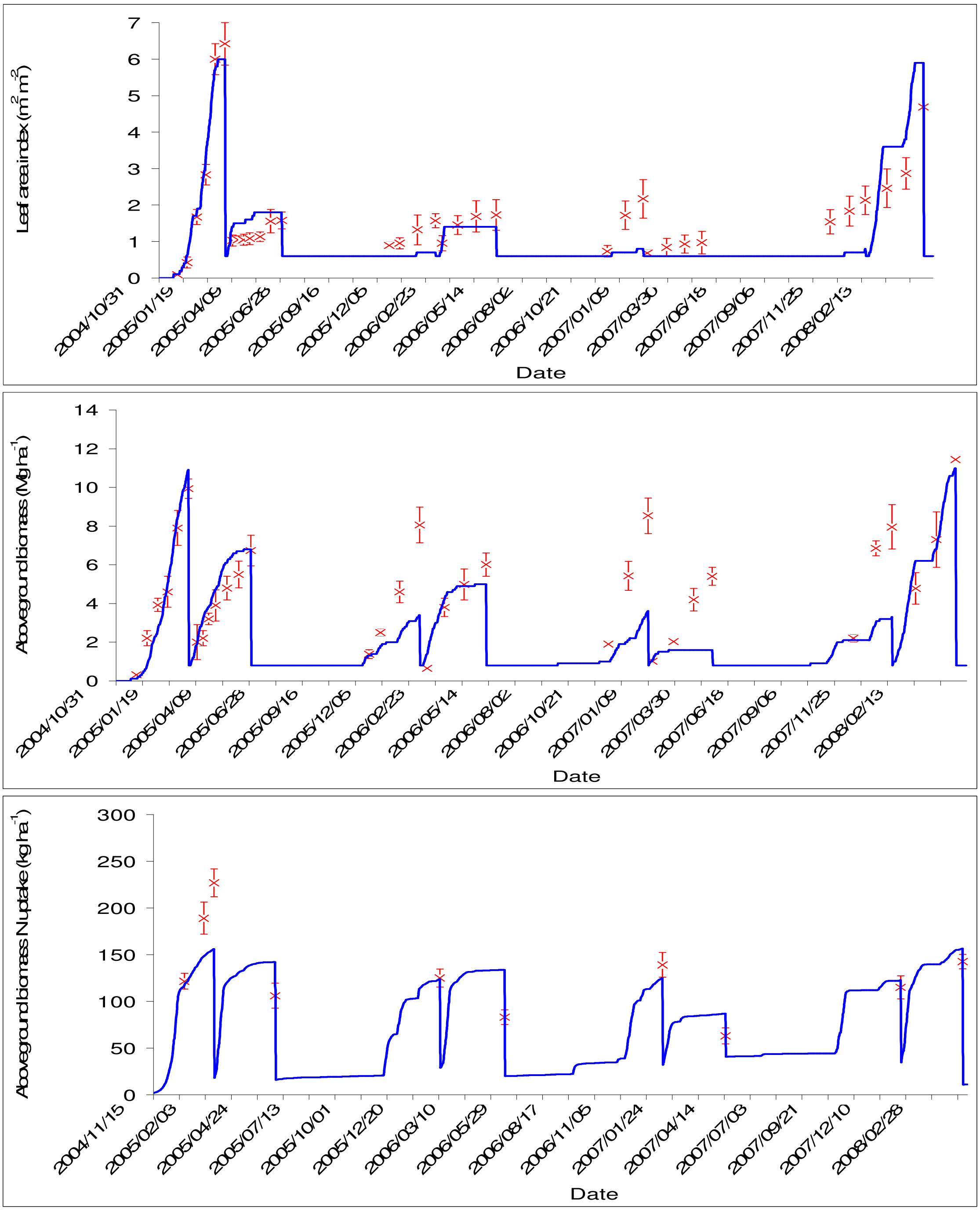

Figure 7.7 Simulated (solid lines) and measured values (symbols with standard deviation) of weeping lovegrass leaf area index (a), aboveground biomass (b), and aboveground biomass N uptake (c) for the 16 Mg ha^{-1} yr^{-1} sludge treatment during the 2004/05 to 2007/08 study period (without updating soil water).

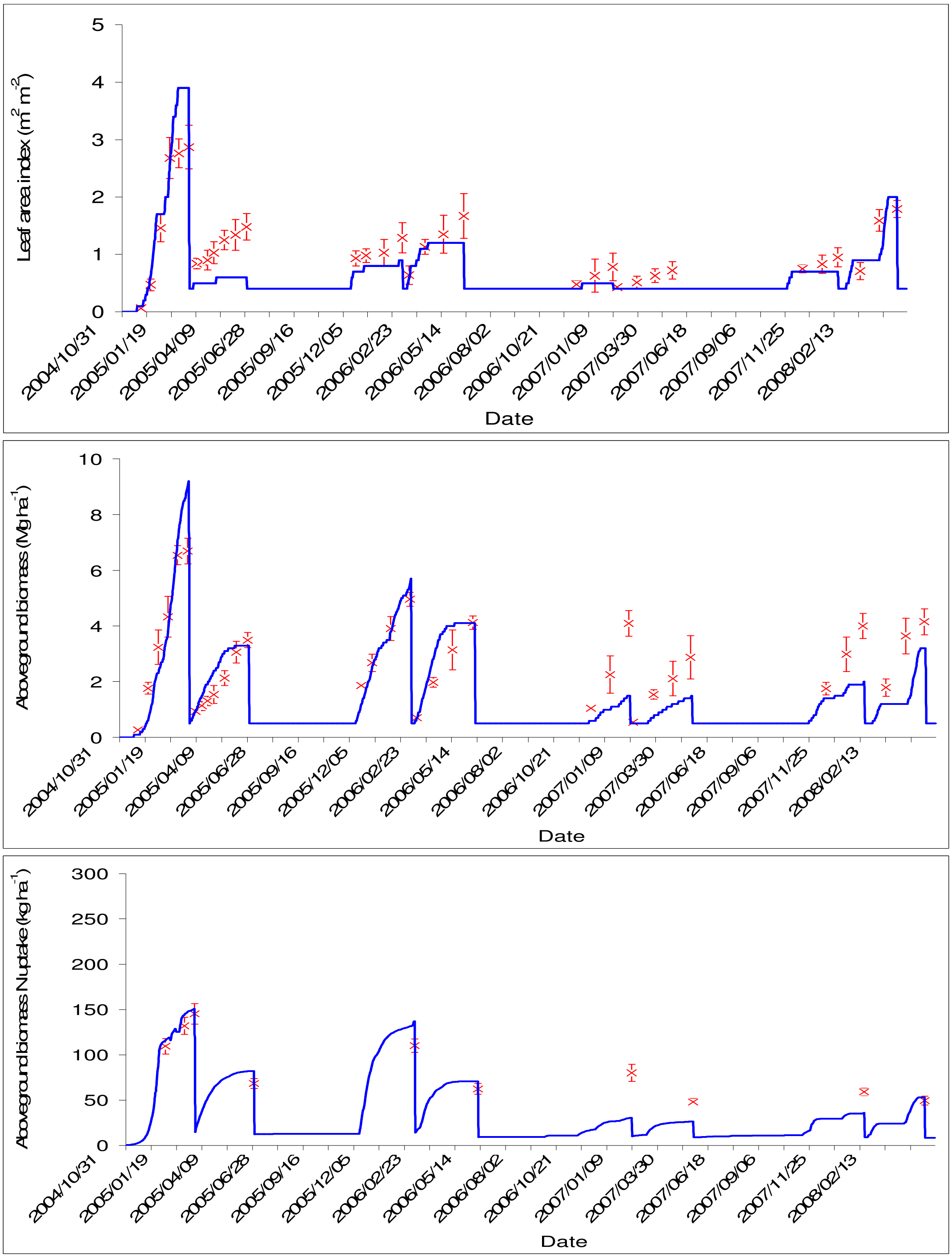

Figure 7.8 Simulated (solid lines) and measured values (symbols with standard deviation) of weeping lovegrass leaf area index (a), aboveground biomass (b), and aboveground biomass N uptake (c) for the control treatment (0 nutrients applied) during the 2004/05 to 2007/08 study period (without updating soil water).

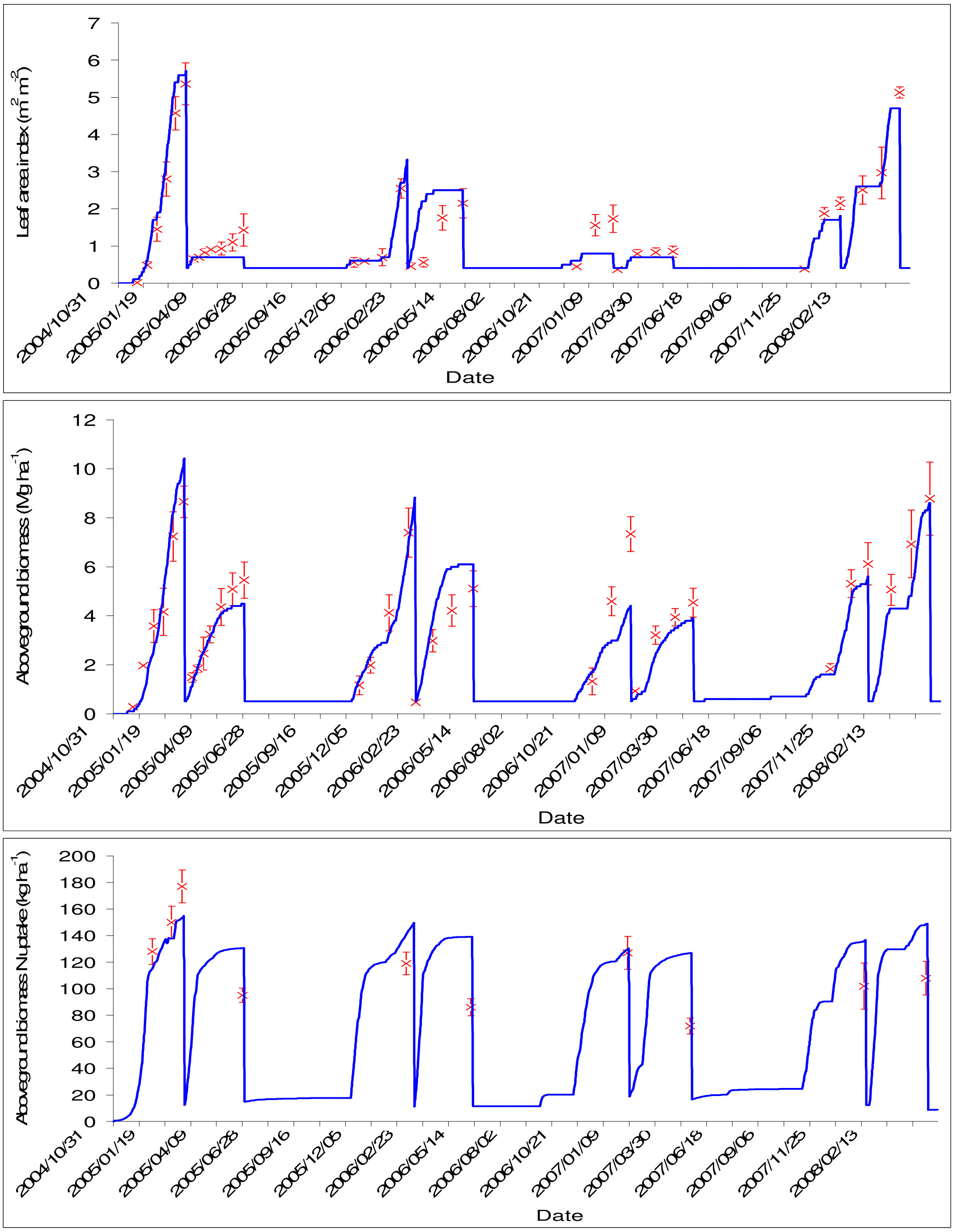

Figure 7.9 Simulated (solid lines) and measured values (symbols with standard deviation) of weeping lovegrass leaf area index (a), aboveground biomass (b), and aboveground biomass N uptake (c) for the 8 Mg ha^{-1} yr^{-1} sludge treatment during the 2004/05 to 2007/08 study period (without updating soil water).

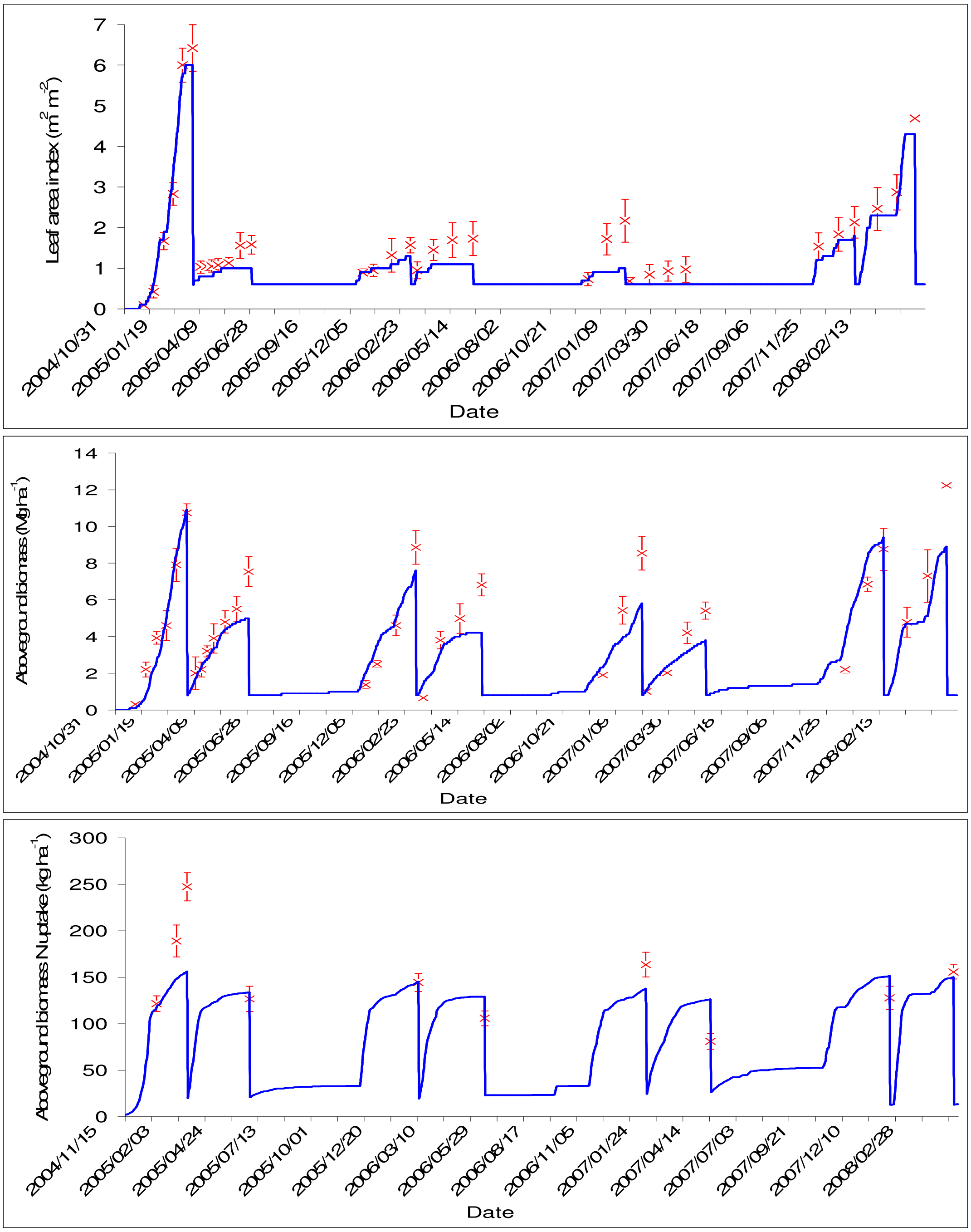

Figure 7.10 Simulated (solid lines) and measured values (symbols with standard deviation) of weeping lovegrass leaf area index (a), aboveground biomass (b), and aboveground biomass N uptake (c) for the 16 Mg ha^{-1} yr^{-1} sludge treatment during the 2004/05 to 2007/08 study period (without updating soil water).

7.3 Conclusions

The model was successfully calibrated for maize, oats, and weeping lovegrass. The model simulated both LAI, aboveground biomass, grain yield, aboveground biomass N uptake, and grain N uptake with acceptable accuracy. Model corroboration conducted using three year independent sets of data also proved accuracy of the model in simulating the above mentioned variables for dryland maize and irrigated maize-oat rotation. The model shows promise as a decision support tool. For dryland pasture, the model predicted similar variables of interest with lower accuracy for long-term simulations. The simulation was improved with updating profile water content after every hay cut. This was mainly because the model does not simulate long-term perennial grass growth mechanistically, and the model needs to be improved. Model accuracy in predicting nitrate leaching from agricultural lands treated with sludge should, however, be tested using data collected from controlled systems such as drainage lysimeters.

REFERENCES

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CHAPTER 8

CONCLUSIONS

Sludge applied at double the old 8 Mg ha^{-1} limit significantly increased grain and forage yield in two of the three years under dryland maize and in all of the three years studies for the irrigated maize-oat rotation. Grain and forage yield of irrigated maize exhibited a decreasing trend over time, due to the greater crop N uptake than that supplied with sludge. In contrast, under dryland maize cropping, a net positive total N accumulation was apparent for sludge rates of 8 Mg ha^{-1} and higher. Nitrogen exported in the forage was about twice that of the grain, under both dryland and irrigated conditions. Generally, N exported in the forage from the irrigated rotation was at least three times higher than similar treatments under dryland maize forage production. Soil solution samples collected from wetting front detectors at 0.3 and 0.6 m depths indicated higher nitrate leaching risks from inorganic fertilizer treatments than from the 16 Mg ha^{-1} sludge treatment, usually shortly after fertilizer applications. Residual nitrate after crop harvest in the soil profile of the 16 Mg ha^{-1} dryland maize treatment was higher than the irrigated maize-oat rotation treatment having the same sludge application. Nitrogen mineralization from sludge could, however, take several years before reaching steady-state conditions. Therefore, long-term model simulations across a range of soil types, sludge N concentrations, and sludge qualities should be conducted. Sludge applications at all rates studied resulted in the accumulation of total P and Bray-1P, both for dryland and irrigated cropping systems. The only exception was Bray-1P in the 8 Mg ha^{-1} irrigated rotation which remained similar throughout the study.

Doubling of the 8 Mg ha^{-1} sludge limit increased weeping lovegrass hay yield, crude protein content, and water use efficiency. Sludge applied at the 8 Mg ha^{-1} limit was not sufficient to satisfy the demand of weeping lovegrass, resulting in crop N uptake from soil reserve and a decline in total profile N. Sludge applied at 16 Mg ha^{-1}, however, exceeded crop N demand resulting in the accumulation of total N, but not residual nitrate and ammonium. The low residual nitrate and ammonium together with the low nitrate concentration in soil solution collected from the 0.3 m deep wetting front detectors of the 16 Mg ha^{-1} treatment indicated low risk of ground water pollution through nitrate leaching. Total P accumulation was evident for all sludge rates. Bray-1P decreased as sludge rate increased up to 8 Mg ha^{-1}. This is in contrast to similar treatment under dryland maize cropping. Sludge applied at 16 Mg ha^{-1}, however, increased Bray-1P significantly across years.

Increasing sludge application rates up to 67 Mg ha^{-1} significantly improved turf establishment rate and colour. The ability of sods to remain intact during handling improved as the sludge application rate increased to 33 Mg ha^{-1}, but deteriorated at higher rates. High loading rates of 100 Mg ha^{-1} minimized soil loss from the site but caused unacceptably high leaching losses.

It was evident from this study that N removal varied across a range of cropping systems, seasons, and management practices. In addition, N content varies across a range of sludge types and N mineralization from sludge could take several years before reaching steady state conditions. Therefore, a dynamic, mechanistic decision support tool is needed in order to accommodate the interaction between the various factors involved.

The N sub-routine incorporated into the existing SWB model was successfully calibrated with acceptable accuracy for dryland maize, the irrigated maize-oat rotation, and dryland pasture. The model was tested against independent sets of data and predicted leaf area index, aboveground biomass, grain yield, aboveground biomass N uptake, and grain N uptake with acceptable accuracy. The model predicted the above mentioned variables for dryland pasture with low accuracy due to the non mechanistic approach followed by the model when simulating perennial grasses.

Municipal sludge could be applied above the 8 Mg ha^{-1} limit to satisfy the high N demand of intensive cropping systems such as the irrigated maize-oat rotation and dryland pasture with minimal environmental impacts through nitrate leaching. Soil P accumulation and its availability should, however, be monitored for overall environmental sustainability. Ideally the upper sludge limit to satisfy crop N demand should be dynamic and could exceed the old 8 Mg ha^{-1} upper limit. But ultimately the maximum amount of sludge applied to a site will depend on the accumulation of total and available P and the risk this poses for pollution, as long as the threat from other pollutants is minimal.

According to this study, anaerobically digested paddy dried sludge could be applied as high as 33 Mg ha^{-1} for turfgrass sod production - four times higher than the 8 Mg ha^{-1} limit. This rate improved turf growth and quality with minimal environmental impact through nitrate leaching.

This study will help to improve the local knowledge of the benefits and disadvantages of sludge application in agricultural lands. Moreover, results from this study will contribute to the plan to update the current guideline on agronomic crops (Volume 2 (Snyman and Herselman, 2006)) and the development of Volume 4 on beneficial use at high loading rates, which is still under development.

Results from this study confirm previous studies showing total P accumulation in N based agricultural sludge management practices. Results will also contribute to the few field scale long term P availability studies on Fe salt treated sludges applied to agricultural land at various rates, different cropping systems, and management practices. The N model looks promising especially for dryland maize and irrigated maize-oat rotation to be used as decision supporting tool for sustainable sludge use in agricultural lands.

Recommendations for future research include:

- A monitoring protocol to complement the decision support system, to ensure that leaching losses were kept within reasonable limits.
- The maximum number of years which sludge could be left without incorporation under perennial pasture grasses with minimal environmental impacts through runoff nutrient losses needs investigation.
- The potential for pollution through nitrate leaching as well as P and nitrate runoff losses from turfgrass established at new sites from sods treated with high sludge rates needs investigation.
- Updating the SWB model to simulate perennial grasses mechanistically.

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