# CHAPTER 7

# ANALYSIS OF NITROGEN AND PHOSPHORUS LEACHING FROM DRYLAND AND IRRIGATED CROPPING SYSTEMS USING LONG-TERM MODELLING

***ABSTRACT***

*Cropping systems can potentially contribute high loads of non-point source (NPS) nitrogen (N) and phosphorus (P) pollution to ground and surface waters. Quantifying these contributions is however highly challenging. Long-term modelling at the local scale for a hypothetical field located on the South African Highveld was used to assess the potential contribution of irrigated and dryland crop production to N and P leaching losses in a monoculture maize cropping system. As irrigated systems present more management options, the effect of a 'room for rain' irrigation strategy and a maize-wheat crop rotation system on reducing N and P leaching losses were also investigated. Over a 30 year simulation period, irrigated crop production was observed to leach 480% more N and 420% more P than dryland production. A 'room for rain' irrigation strategy was able to reduce N leaching by 12% and P leaching by 14% compared to irrigating to field capacity. Despite increased irrigation and fertilization input requirements for a crop rotation system, significant reductions in N (23%) and P (24%) leaching losses were observed for this system compared to the monoculture system. From this trial it is clear that long-term modelling can be used effectively to investigate N and P leaching losses from different cropping systems and identify appropriate mitigation measures.*

## 7.1 INTRODUCTION

Loss of nutrients from agricultural systems to waterways is a world-wide problem that can lead to eutrophication and jeopardize aquatic ecosystems and fresh water quality (Matson et al., 1997). Nitrogen (N) and phosphorus (P) are most frequently the limiting nutrients for algal growth and are therefore implicated as the primary nutrients leading to eutrophication (Walmsley, 2000). Negative spin-offs from eutrophication and toxic algae growth include: taste and odour problems in drinking water, oxygen depletion, increased fish and invertebrate mortality, waterway clogging interference in irrigated agriculture and recreational activities, increased treatment costs and a decline in aesthetic conditions (Toerien, 1974; Dunst et al., 1974). High nitrate ($NO_3^-$) levels in drinking water can also be hazardous to infants and livestock (Tredoux, 1993). Furthermore, N and P loss from agricultural soils can result in unwanted environmental impacts and substantial economic loss for farmers. N and P can be exported to waterways in inorganic or organic forms via runoff or leaching, making this type of pollution very difficult to measure.

The replacement of natural vegetation with cropping systems can drive major changes in water balances and cause the redistribution of water and solutes in the landscape (Keating et al., 2001). It can be commonly expected that irrigated and dryland cropping systems will have different water and nutrient balances. According to Bristow (2004), most current irrigation systems can be characterized by uniformity, discontinuity in nutrient dynamics (large fertilizer inputs at planting and large removal at harvest), excess deep drainage, and rising water tables and salinisation. The close spatial proximity of irrigated cropping systems to water sources results in these systems often having higher risk with regard to polluting potential due to the likelihood of increased delivery of nutrients to ground and surface waters. The focus of concern will lie with downstream water and ecological systems, as most water supply dams are usually upstream of irrigated areas. For these reasons, an increase in irrigation area can be expected to intensify the NPS nutrient pollution problem.

In developing countries, irrigated land consists of 20% of total arable land but produces 40% of all crops and close to 50% of cereal production (FAO, 2003). Further agricultural production intensification will be required to feed the increasing world population. According to the FAO, between the years 1960 and 2000, nitrogenous fertilizer consumption increased 7-fold and phosphate fertilizer consumption increased 3-fold, while total irrigated area doubled between 1960 and 1999 (http://faostat.fao.org). Tilman et al. (2001) used past global trends and their dependence on population size and GDP to obtain trajectories for global irrigated area and N and P fertilizer consumption in 2020 and 2050. The authors estimated that global N and P fertilization would increase 1.6- and 2.7-fold by 2020, and 1.9- and 2.4-fold for 2050, respectively, from 2000 values. They also estimated that irrigated area will increase 1.3-fold by 2020 and 1.9-fold by 2050, with most increases occurring in Latin America and sub-Saharan Africa. While statistics on the breakdown of nutrients used on dryland versus irrigated agriculture are not readily available one can assume that irrigated cropping systems will generally receive higher fertilizer inputs due to higher target yields. These large projected increases could have significant environmental impacts (Tilman et al., 2001), and necessitate improved mitigation measures.

High N leaching potential is often expected in relatively arid areas where intensively managed fruit and vegetable crops are common, as mild winters permit crop residue decomposition, and heavy rainfall can occur within a few winter months, promoting leaching (Coppock and Meyer, 1980). Similarly, leaching is also more predominant in coarse than fine textured soils. An array of studies investigating $NO_3^-$ leaching have produced a wide range of results depending on experimental conditions, with amount of $NO_3^-$ leached usually related to amount of fertilizer N applied and the volume of deep percolation. Nitrate losses greater than 100 kg N $ha^{-1}$ have been observed in semi-arid surface irrigated areas in Spain and the USA (Causapé et al., 2004). Sexton et al. (1996) observed that the majority of $NO_3^-$ leaching in a season occurred during only two major rainfall periods, highlighting the importance of specific leaching events in a season. In the US, higher groundwater $NO_3^-$ concentrations are more often observed in areas under irrigation than in areas with no irrigation (Follet and Hatfield, 2004).

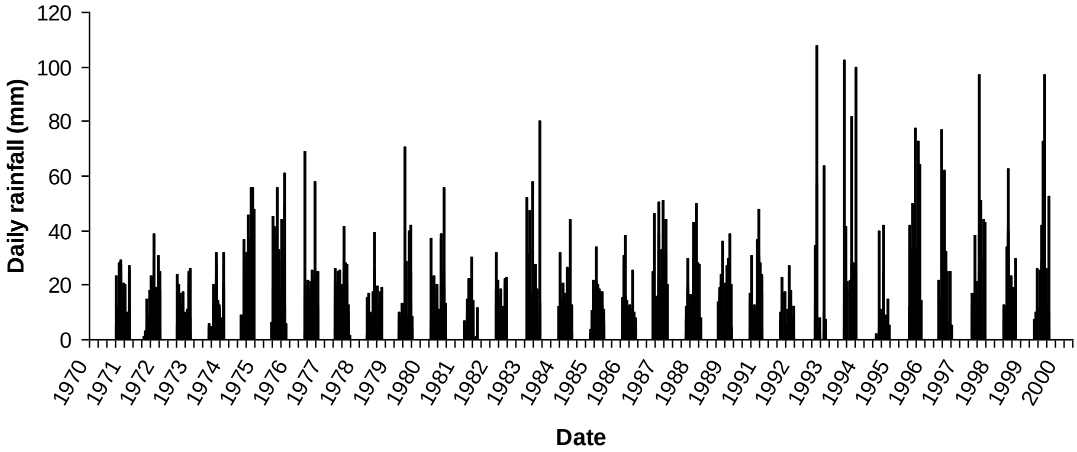
The movement of P through the soil profile is less well documented than P movement in surface runoff (Bush and Austin, 2001), but recently more attention is being given to P leaching. Toor et al. (2005) report that significant amounts of P can be lost shortly after P fertilizer applications when preferential transport takes place through cracks, root holes and worm borings in the soil. However, P leaching is usually minimal in soils through which water moves very slowly and there is prolonged contact with the soil matrix (Djodjic et al., 2004).

From field scale nutrient balances, Annandale and du Preez (2005) concluded that dryland crop production in South Africa has a limited impact on groundwater nitrate levels, especially on deeper soils. As irrigated systems are often characterized by intensive crops, higher nutrient application rates and wetter systems, it may be expected that these systems are ‘leakier’ relative to dryland production.

The objective of this study was firstly to compare the impact of dryland versus irrigated agriculture on expected N and P leaching losses from cropping systems. As irrigated systems often offer the highest flexibility in terms of mitigation management practices, N and P leaching was further investigated for two additional scenarios, the first employing a ‘room for rain’ irrigation strategy, and the second using a crop rotation strategy. Ultimately, the potential for using a local scale, mechanistic model such as SWB-Sci to estimate N and P leaching and find potential management practices to reduce these types of losses was assessed.

## 7.2 MATERIALS AND METHODS

SWB-Sci is a local scale crop model that can mechanistically model N and P dynamics in cropping systems (see Chapters 4, 5 and 6). The soil water balance is modelled using a simple cascading approach (Campbell and Diaz, 1977), and a daily crop dry matter increment is estimated as being either water supply (Tanner and Sinclair, 1983) or solar radiation limited (Monteith, 1977). This daily dry matter increment is then used to calculate daily crop N and P demand after which the lesser of any N or P stress on crop growth is accounted for through stress factors (see Chapter 5). The model was used to run 30 year simulations for a single dryland and three irrigation scenarios on a hypothetical field in the Bethal area, Mpumalanga, South Africa. The soil profile used in the simulations was based on the soil used in an N and P leaching trial conducted in a drainage lysimeter in Pretoria, South Africa (see Chapter 6). Briefly, the 1.5 m deep soil has a sandy clay loam texture with a clay content of 20% and a sand content of 70%. Soil organic matter ranges from 1.0 to 1.3%, pH($H_2O$) ranges from 5.9 to 6.2, and Bray I P ranges from 20 to 6.6 mg kg$^{-1}$ with depth. Rainfall and $ET_o$ data used in the simulation for the 30 year period are presented in Figure 7.1. No N and P additions via rainfall or irrigation were simulated.

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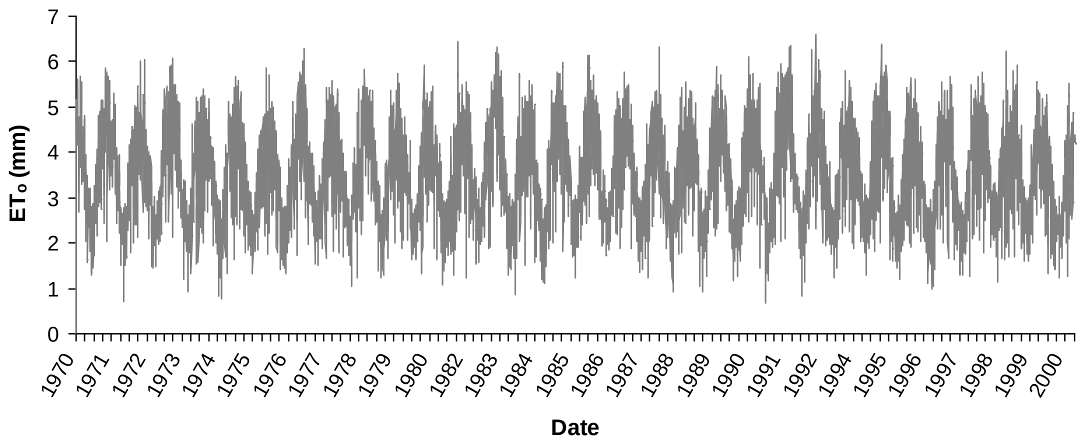


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**Figure 7.1** Daily rainfall (a) and daily $ET_o$ (b) for the Bethal area for the simulation period (1970 -2000)

The first scenario simulated a dryland maize system (DM = dryland maize) totally dependent on rainfall. Following 15 September, daily rainfall was summed and maize was planted immediately after 20 mm of rainfall had occurred. At planting, the crop was fertilized with 40 kg N ha$^{-1}$ in the form of limestone ammonium nitrate (LAN) and 15 kg P ha$^{-1}$ in the form of superphosphate which was banded at a depth of 10 cm.

For the second scenario maize was grown under irrigation (IM = irrigated maize). The crop was planted on 25 October each year and fertilized on this day with 40 kg P $ha^{-1}$ in the form superphosphate banded at 10cm. Nitrogen fertilizer was applied in split applications of 100 kg N $ha^{-1}$ each at plating and 6 weeks after planting. Soil in the root zone was irrigated to field capacity when root zone plant available water (PAW) reached a deficit of 40%.

The third scenario was exactly as for IM, except that instead of irrigating the root zone to field capacity, irrigation was applied to allow for 30 mm of 'room for rain' (IMrr). This strategy was not applied for the initial, establishment phase of the crop when the root zone was irrigated to field capacity.

The fourth scenario (IMwr) was also exactly as for IM, except that a crop rotation system involving wheat was used. Wheat was planted on 1 May of every year and fertilized with 80 kg N $ha^{-1}$ (LAN) and 10 kg P $ha^{-1}$ (superphosphate, banded at 10 cm). A further 60 kg N $ha^{-1}$ was applied 6 weeks after planting. Irrigation scheduling used the same approach as for IM.

Maize and wheat crop parameters were obtained from model calibration and testing work done for a dryland maize and wheat trial receiving different N applications conducted in Glen, near Bloemfontein, South Africa (Schmidt, 1993) and a maize trial receiving different N and P application rates conducted in Kenya (Probert and Okalebo, 1992). For both crops, the radiation use efficiency (kg $MJ^{-1}$) was increased and the day degrees to maturity were decreased to represent cultivars with higher yield potentials and shorter growth durations.

Direct comparisons were made between DM and IM, IM and IMrr and IM and IMwr, and thereafter all four scenarios were considered together.

## 7.3 RESULTS

### 7.3.1 Dryland versus irrigated cropping systems

As expected, final yield data for the 30 year simulation period was observed to be higher and more consistent for the irrigated (IM) than for the dryland (DM) scenario (Figure 7.2). Yields of between 8.9 and 11.6 tons were achieved for the irrigated system, while yield fluctuated from below 0.1 to 8.5 t ha$^{-1}$ for the dryland scenario depending on seasonal rainfall.

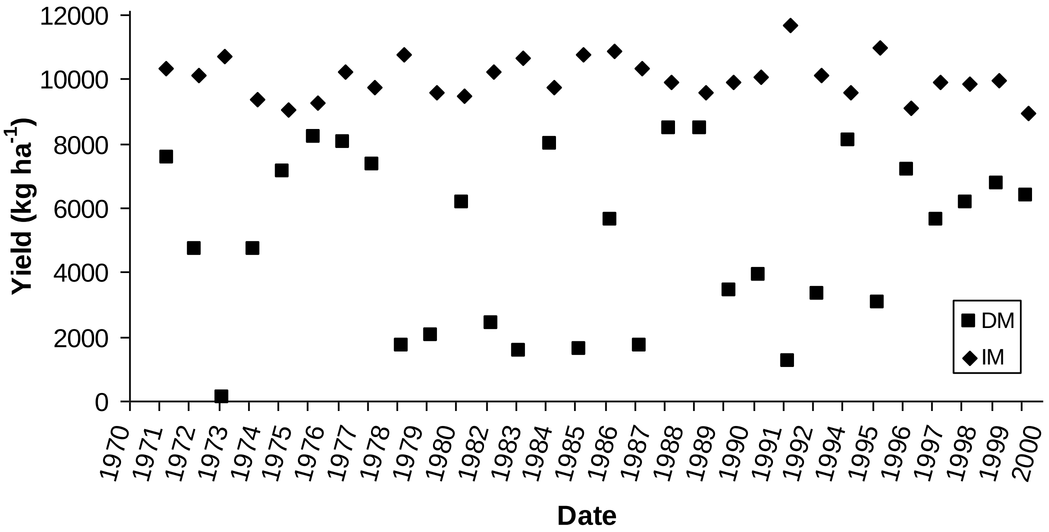



**Figure 7.2** Seasonal yields over the 30 year simulation period for the Dryland Maize (DM) and Irrigated Maize (IM) scenarios

As a result of irrigation leading to a ‘wetter’ soil profile with little additional space for rainfall, higher cumulative profile drainage was simulated for the irrigated scenario than for the dryland scenario (Figure 7.3). Over the 30 year simulation period, in addition to 22029 mm of rainfall, 6328 mm of irrigation was applied resulting in 3495 mm of deep drainage leaving the root zone and 48 mm of runoff for IM. For the dryland scenario, we simulated 787 mm of deep drainage and 17 mm of runoff. No deep drainage occurred over entire growth seasons for long periods, most notably between 1970 and 1983. Irrigation therefore led to a 4.4-fold increase in cumulative deep drainage over the 30 year period.

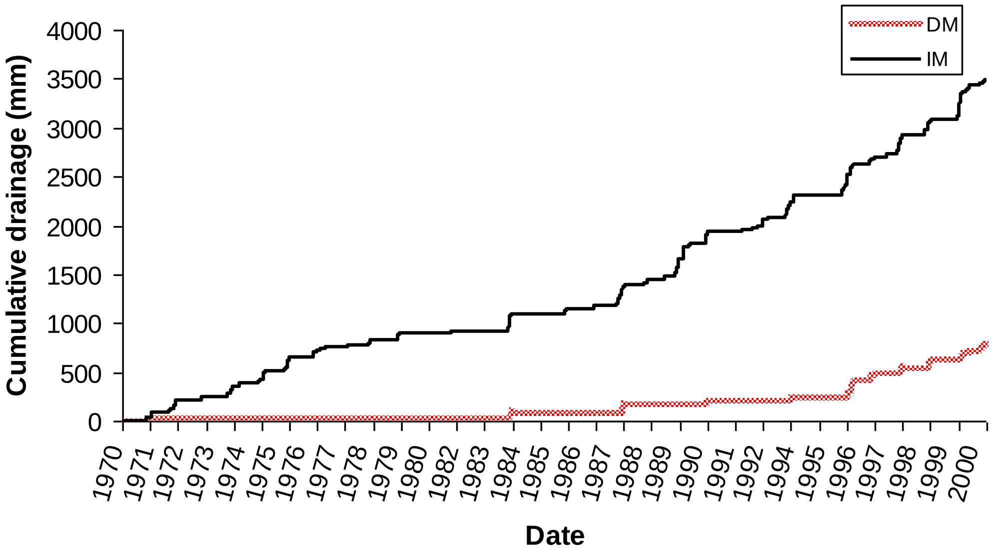
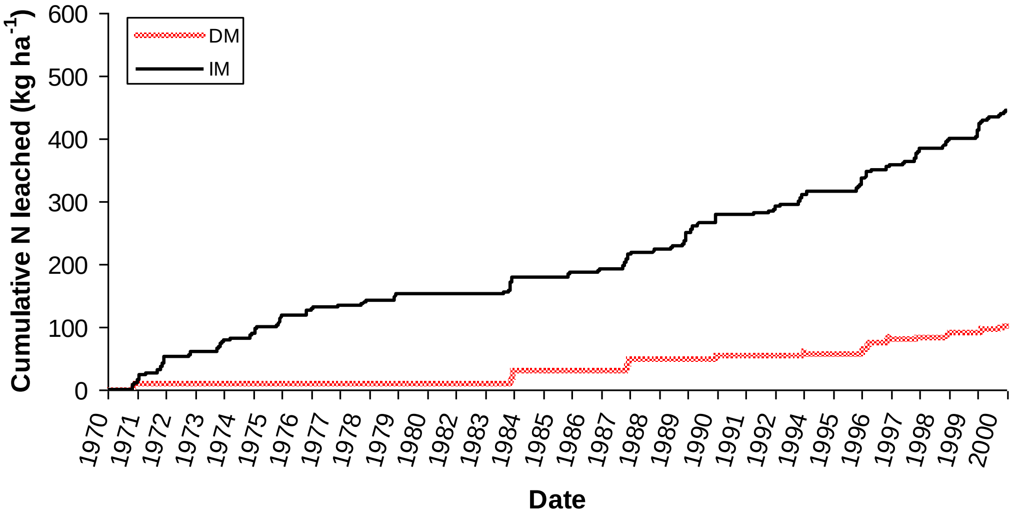



**Figure 7.3** Cumulative deep drainage (mm) over the 30 year simulation period for the Dryland Maize (DM) and Irrigated Maize (IM) scenarios

For the IM scenario, 497 kg N $ha^{-1}$ of the 6000 kg N $ha^{-1}$ applied was estimated to have leached, and for the DM scenario 103 kg N $ha^{-1}$ of the 1200 kg N $ha^{-1}$ applied was simulated to have leached (Figure 7.4). Cumulative N leaching for the irrigation scenario was therefore 4.8-fold higher than for the dryland scenario. For the first 20 years, despite less N fertilizer being applied to the DM than to the IM scenario, higher drainage $NO_3^-$ concentrations were observed for the DM scenario. The highest $NO_3^-$ concentration of 168 mg $l^{-1}$ was observed for the DM scenario in the first deep drainage event following a long period during which no deep drainage occurred. Following the first season, $NO_3^-$ concentrations fluctuated between 40 and 100 mg $l^{-1}$, for the IM scenario. For the DM scenario especially, sudden sharp increases in cumulative N leached highlighted that leaching is clearly event driven.

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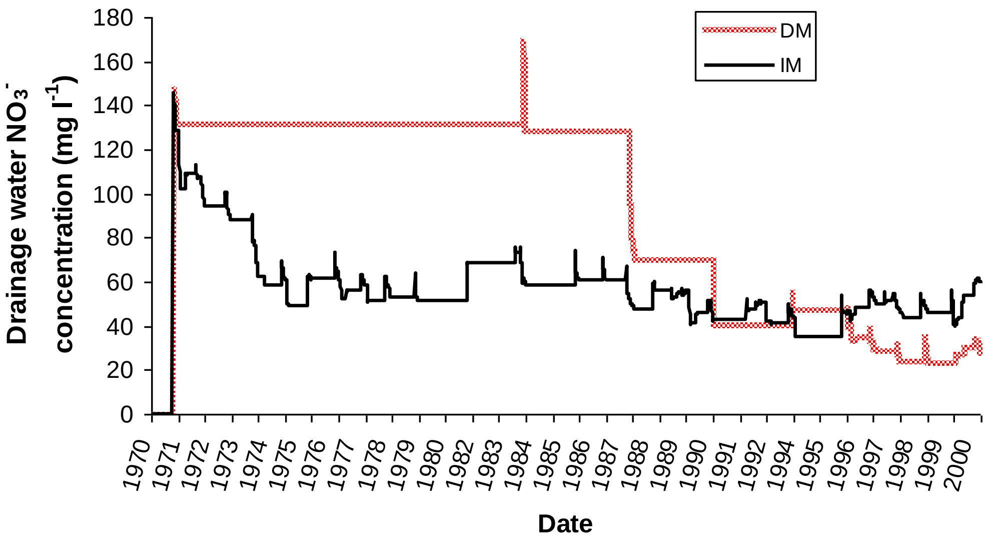


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**Figure 7.4** Cumulative N leached (a) and drainage water $NO_3^-$ concentrations (b) over the 30 year simulation period for the Dryland Maize (DM) and Irrigated Maize (IM) scenarios

Cumulative P leaching over the simulation period is presented in Figure 7.5. For the IM scenario, 88 kg P ha$^{-1}$ of the 1200 kg P ha$^{-1}$ applied was estimated to have leached, while for the dryland scenario, 21 kg P ha$^{-1}$ of the 450 kg P ha$^{-1}$ applied was estimated to have leached over the 30 year period. This represents a 4.2-fold difference between the two scenarios and is reflects the differences in cumulative deep drainage. P concentrations in the drainage water were similar for both scenarios, remaining constant at around 2.6 mg $l^{-1}$. Averaged over the simulation period, 0.7 kg P $ha^{-1}$ $a^{-1}$ was estimated to leach from the dryland scenario and 2.9 kg P $ha^{-1}$ $a^{-1}$ was estimated to leach from the irrigated scenario. For the IM scenario, P leaching was therefore simulated to be slightly above 7.3% of applied fertilizer P.

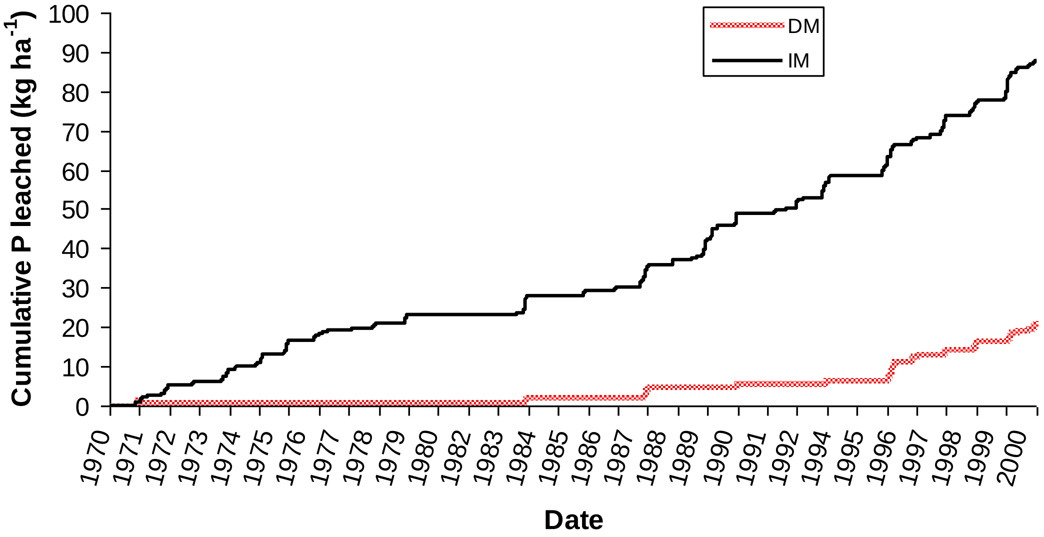



**Figure 7.5** Cumulative P leached over the 30 year simulation period for the Dryland Maize (DM) and Irrigated Maize (IM) scenarios

### 7.3.2 Irrigation scheduling

Applying an irrigation refill strategy that allowed 30 mm ‘room for rain’ (IMrr) had little effect on final yield relative to a strategy that refilled the root zone to field capacity (IM) (Figure 7.6). In several cases yield for IMrr was marginally higher than for IM and this may have been due to slightly less nutrient leaching occurring for the IMrr scenario.

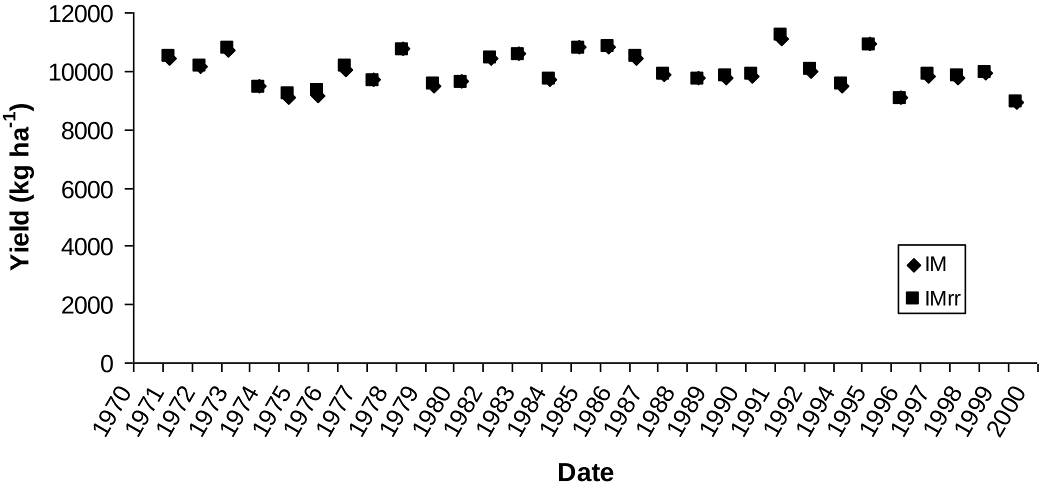



**Figure 7.6** Seasonal yields over the 30 year simulation period for Irrigated Maize (IM) scenarios and Irrigated Maize 'room for rain' (IMrr) scenarios

As expected, deep drainage for the IMrr scenario was less than for the IM scenario. Cumulative drainage at the end of the 30 year simulation period was 2986 mm for the IMrr scenario and 3495 mm for the IM treatment (Figure 7.7). This equates to a yearly average of 17 mm less deep drainage occurring for the IMrr scenario, or a 15% reduction in drainage compared to the IM scenario.

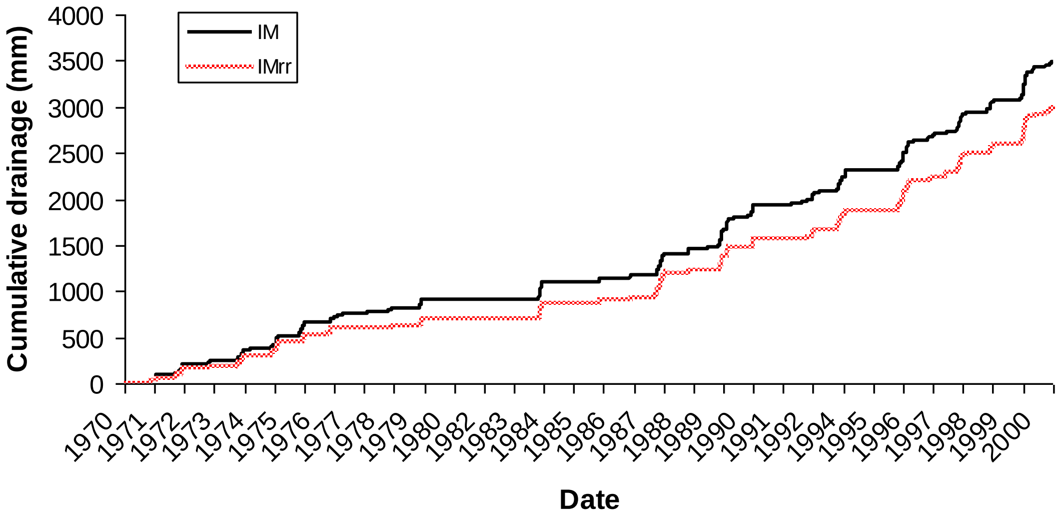



**Figure 7.7** Cumulative deep drainage (mm) over the 30 year simulation period for the Irrigated Maize (IM) and Irrigated Maize 'room for rain' (IMrr) scenarios

While the 'room for rain' strategy was not judged to be highly effective in reducing profile drainage over the long-term, it is important when designing and implementing management strategies to understand the implications of seasonal variations. To explore this two contrasting seasons were analyzed more closely. Cumulative drainage data for a selected period during the 1975/76 maize growth season is presented in Figure 7.8. During this season, the 'room for rain' strategy clearly contributed to reducing total drainage as the drainage that did take place occured later in the season for the IMrr than for the IM scenario, and at the end of the season there was 50 mm less drainage for the IMrr scenario than for the IM scenario. Considering that over the 30 year simulation period, drainage was observed to be 509 mm less for the IMrr than for the IM scenario, the 1975/76 growth season represents 10% of the total over the 30 year simulation period. This again highlights the significance of particular events, and the danger of relying solely on averages.

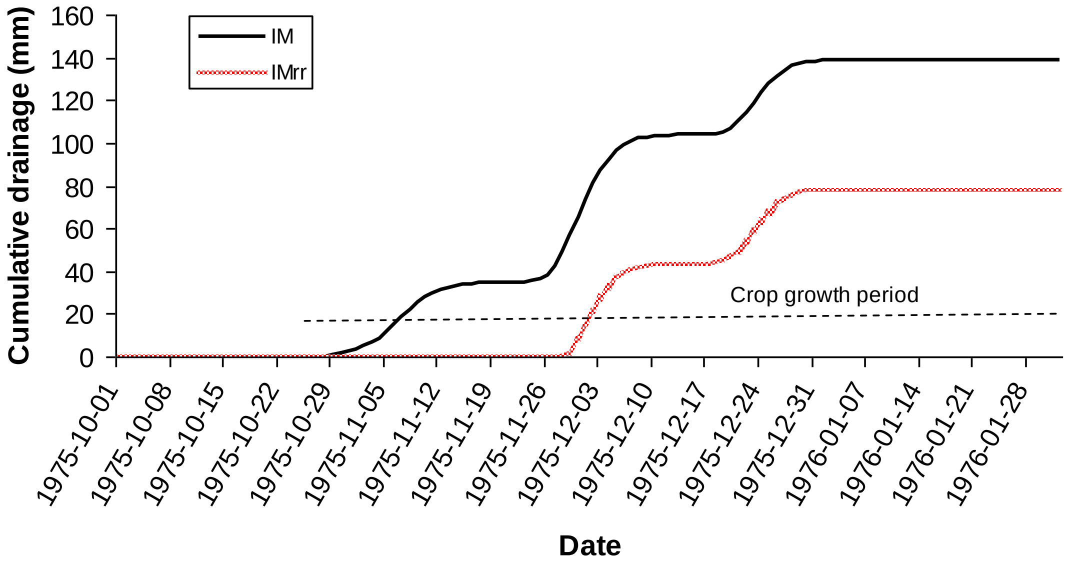
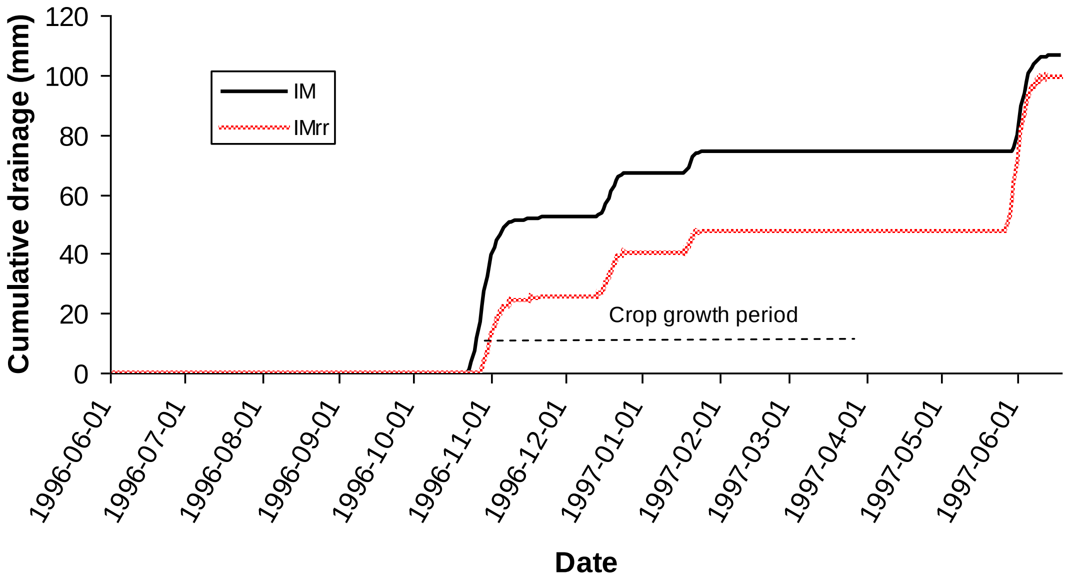



**Figure 7.8** Cumulative deep drainage (mm) over a selected period within the 1975/76 maize growth season

For the 1996/97 growth season, the 'room for rain' strategy was observed to be much less effective in reducing drainage. On closer inspection of the deep drainage for the time period, it was observed that during the actual maize growth season, the 'room for rain' strategy led to a 27 mm reduction in deep drainage. The IMrr strategy which requires more frequent irrigation applications, in this case led to a wetter soil profile at the end of the growth season (Figure 7.9), and as a result rainfall that occurred after the crop was harvested resulted in more drainage from the IMrr scenario than from the IM scenario. Considered over a longer period, the 'room for rain' strategy only led to an 8 mm decrease in cumulative drainage, therefore.

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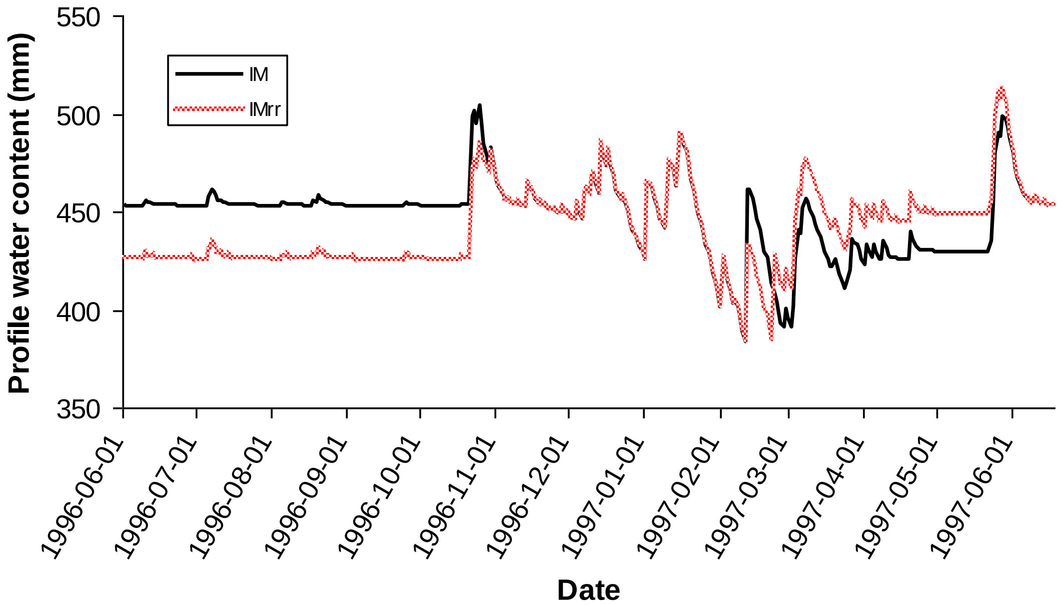


(b)

**Figure 7.9** Cumulative deep drainage (mm) (a) and profile water content (b) over a selected period within the 1996/97 maize growth season

As with drainage volumes from the two scenarios, cumulative N leaching was very similar. After the 30 year simulation period, the 'room for rain' strategy led to a 60 kg $ha^{-1}$ decrease in N leaching, from 497 to 437 kg N $ha^{-1}$ (Figure 7.10). The 'room for rain' strategy was therefore only effective in reducing N leaching by 2 kg $ha^{-1}$ $a^{-1}$, which represents a 13% reduction per year. Similar to N leaching, the 'room for rain' strategy led to a very small decrease in P leaching of 12 kg $ha^{-1}$ over the 30 year simulation period.

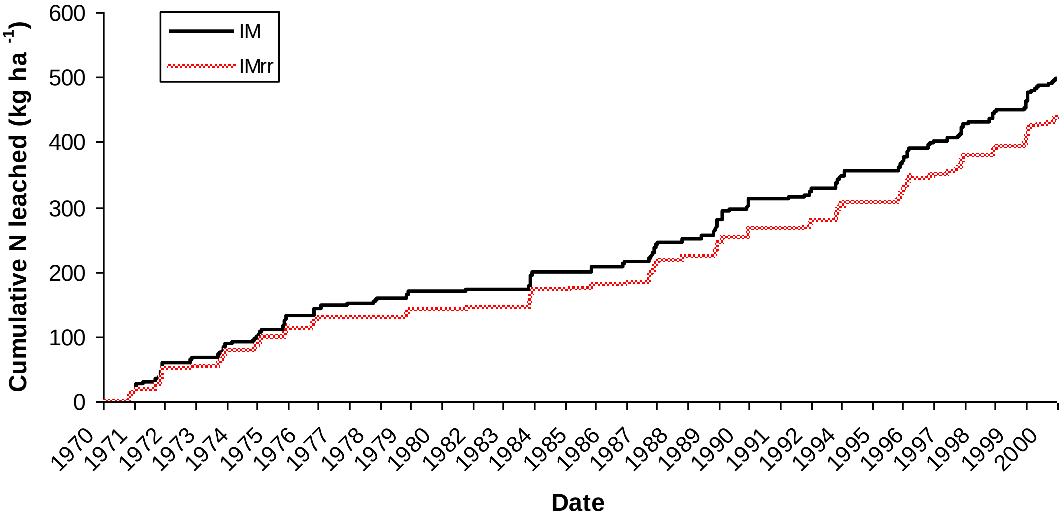


**Figure 7.10** Cumulative N leached over the 30 year simulation period for the Irrigated Maize (IM) and Irrigated Maize 'room for rain' scenarios

### 7.3.3 Crop rotation

Maize yields were observed to be very similar for the monoculture (IM) and crop rotation (IMwr) scenarios (Figure 7.11). In some years, yields for the IMwr scenario were observed to be slightly higher than for the IM scenario, and this may be due to the excess N and/or P fertilizer that was applied to the wheat crop for the IMwr scenario. For the irrigated wheat crop, yields were observed to range between 5.5 and 8.0 t $ha^{-1}$.

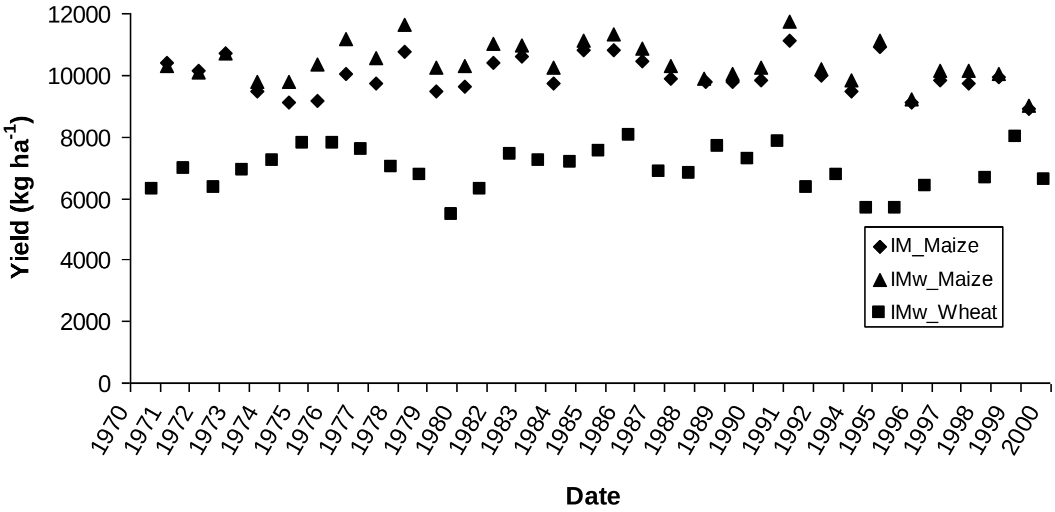


**Figure 7.11** Seasonal yields over the 30 year simulation period for the Dryland Irrigated Maize (IM) and Irrigated Maize-wheat rotation (IMwr) scenarios

Using a crop rotation system with wheat grown over the winter season clearly reduced seasonal profile drainage in comparison to maize monoculture (Figure 7.12). In comparison to the 3495 mm of cumulative drainage that occurred for the IM scenario, 2584 mm cumulative drainage was simulated for the IMwr scenario, representing a 911 mm reduction. This is despite an additional 10108 mm of irrigation water being applied for the IMwr scenario. Using a crop rotation system therefore resulted in an average of 30 mm $a^{-1}$ less deep drainage than for a monoculture system, indicating that a significant amount of drainage was likely occurring before or after the actively growing maize crop season.

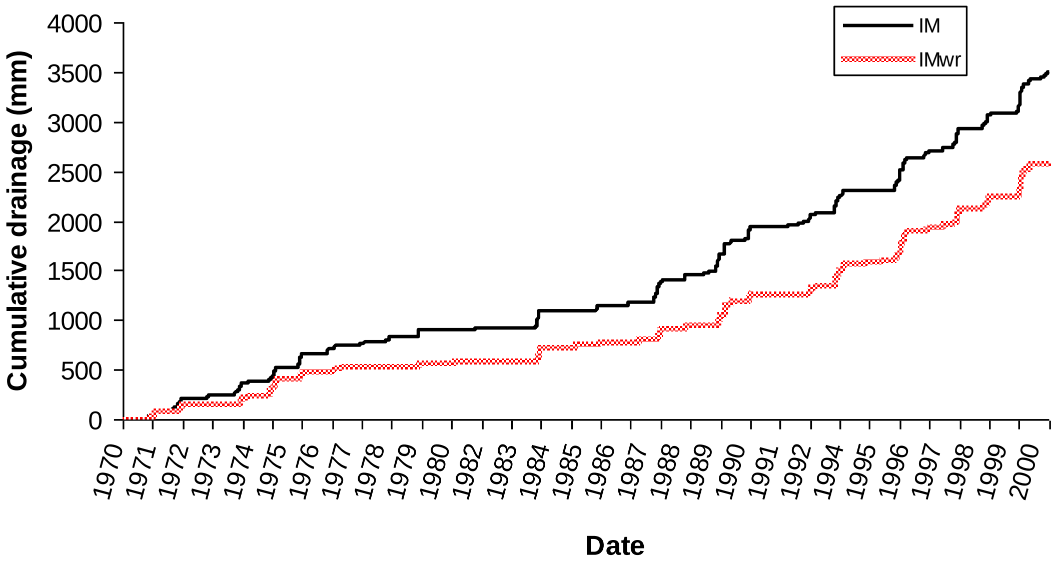


**Figure 7.12** Cumulative deep drainage (mm) over the 30 year simulation period for the Irrigated Maize (IM) and Irrigated Maize-wheat rotation (IMwr) scenarios

As a result of decreased drainage volumes for the IMwr scenario, cumulative N leached was also reduced for this scenario; 497 to 383 kg ha$^{-1}$, a 114 kg ha$^{-1}$ reduction over the 30 year period (Figure 7.13). This represents a greater reduction in N leaching than was achieved for the IMrr scenario.

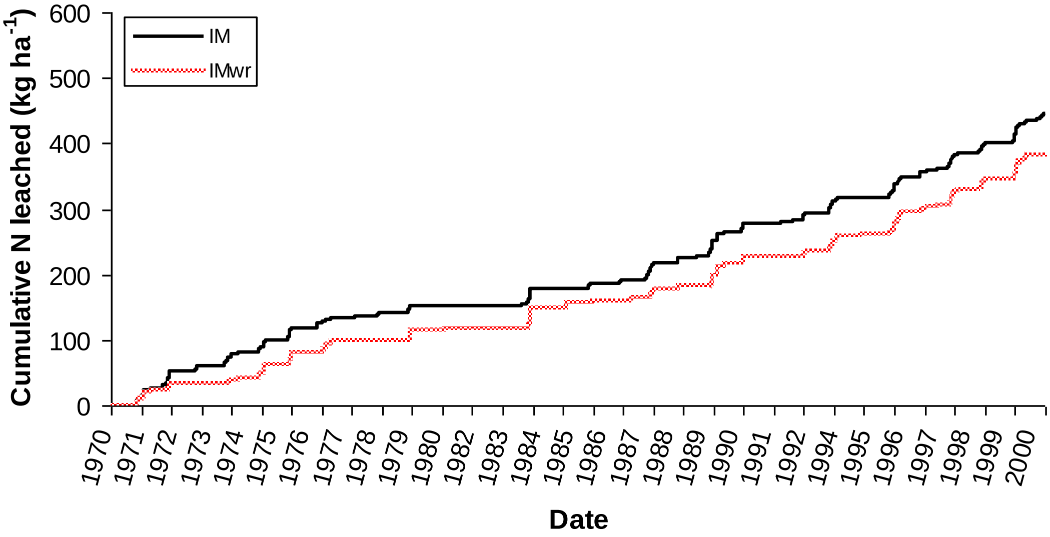


**Figure 7.13** Cumulative N leached over the 30 year simulation period for the Irrigated Maize (IM) and Irrigated Maize-wheat rotation (IMwr) scenarios

Cumulative P leached was also reduced, from 88 kg ha$^{-1}$ for scenario IM to 67 kg ha$^{-1}$ for scenario IMwr (Figure 7.14). Reductions of N and P leaching of 23 and 24%, respectively, were therefore similar and closely correlated to the 26% reduction in cumulative deep drainage.

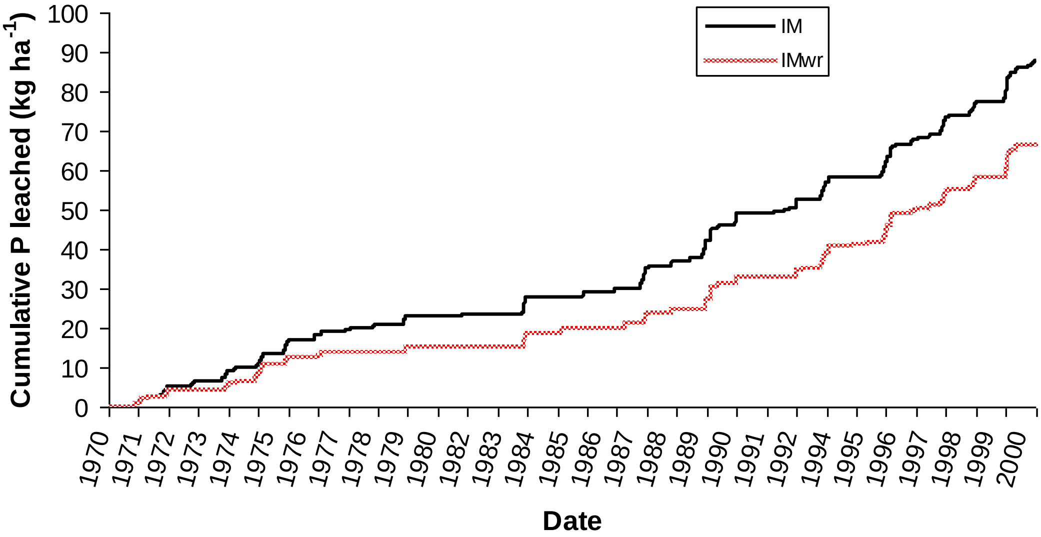


**Figure 7.14** Cumulative P leached over the 30 year simulation period for the Irrigated Maize (IM) and Irrigated Maize-wheat rotation (IMwr) scenarios

## 7.4 OVERVIEW AND DISCUSSION

The highest N and P leaching losses occurred for the IM scenario, while the lowest occurred for the DM scenario (Table 7.1). Compared to the IM scenario, using a 'room for rain' irrigation strategy reduced N leaching by 12%, while using a crop rotation system reduced N leaching by 23%, despite much higher overall irrigation and N and P applications. Correspondingly, P leaching loads were reduced by 14 % for IMrr and by 24% for IMwr.

**Table 7.1** Cumulative water, N and P additions and losses for the IM, DS, IMrr and IMwr scenarios after the 30 year simulation period

| | DM | IM | IMrr | IMwr |
|---|---|---|---|---|
| **Rainfall (mm)** | 22 029 | 22 029 | 22 029 | 22 029 |
| **Irrigation (mm)** | 0 | 6328 | 5916 | 16 436 |
| **Drainage (mm)** | 787 | 3495 | 2986 | 2584 |
| **Runoff (mm)** | 17 | 48 | 17 | 79 |
| **Transpiration (mm)** | 9206 | 12 729 | 17 | 23573 |
| **Evaporation (mm)** | 11 199 | 11 107 | 11 190 | 10867 |
| **Yield (kg ha$^{-1}$)** | 6273 | 9995 | 10 017 | 10 414/6939* |
| **N fertilization (kg ha$^{-1}$)** | 1200 | 6000 | 6000 | 10200 |
| **P fertilization (kg ha$^{-1}$)** | 450 | 1200 | 1200 | 1500 |
| **N removed (kg ha$^{-1}$)** | 3119 | 4848 | 4864 | 8836 |
| **P removed (kg ha$^{-1}$)** | 230 | 337 | 336 | 595 |
| **N leached (kg ha$^{-1}$)** | 103 | 497 | 437 | 383 |
| **P leached (kg ha$^{-1}$)** | 21 | 88 | 76 | 67 |

*Values for maize/wheat

Although average yield for the IM scenario was observed to be 160% higher than for the DM scenario, N leaching was observed to be 482% higher and P leaching 420% higher for the IM scenario. From an environmental standpoint, farming larger surface areas under dryland production will therefore potentially pollute less than irrigated production on smaller surface areas. High yield fluctuations due to unreliable rainfall and limited land availability disfavour such an approach, however. Overall therefore, the IMwr crop rotation system can be expected be more efficient with regards to producing high yields while maintaining relatively low N and P leaching rates. But although crop rotation was observed to play an important role in retaining N in the system, when the crop senesces the N is returned to the soil and can contribute to N leaching (Goulding, 2000). An additional risky period when a second crop's residues are present on the soil will potentially be included therefore. The same will apply for P. The use of a simple cover crop will be expected to have the same beneficial effects as a crop rotation system on reducing N and P leaching.

For scenarios IM, IMrr and IMwr, more N was applied as fertilizer than was removed in the grain of the crop, but this was not the case for the DM scenario in which a net ‘mining’ of soil N was observed. Therefore although the lowest leaching losses were simulated for this scenario, a depletion of soil organic matter over time can be expected and the long-term sustainability of such a system requires further investigation. In practice, P fertilization is often adjusted according to soil P tests which give an indication of crop available P in the soil. It is therefore plausible that P fertilization could have been reduced for the scenarios investigated in this study if there was a build up of P, and this may have reduced the amount of P leaching from the profile. Ultimately, the aim is to supply nutrients as and when needed to match crop demand in order to minimize leaching losses.

The South African Department of Water Affairs and Forestry set effluent discharge standards for $NO_3^-$ at 44.3 mg $l^{-1}$ and for P at 1 mg $l^{-1}$ (DWAF, 1996). Whether such a discharge standard should apply to leaching from cropping systems is debatable. $NO_3^-$ concentrations in the leachate from IM, IMrr and IMwr were observed to fluctuate between 40 and 100 mg $l^{-1}$. The highest drainage water $NO_3^-$ concentration of 168 mg $l^{-1}$ was observed for the DM scenario following a long period in which no drainage took place. Consequently, although dryland exports a smaller long-term N load, a build-up of N deeper in the soil profile during the periods when no drainage occurs can lead to high $NO_3^-$ fluxes entering water systems when drainage finally does occur. For P, leaching concentration for all scenarios remained relatively stable, ranging from 2.3 mg $l^{-1}$ to 2.7 mg $l^{-1}$.

Other forms of N loss from cropping systems such as denitrification and volatilization were not considered in this paper. It is plausible that higher gaseous losses could have been expected from the more intensively fertilized scenarios, including higher denitrification from the irrigated scenarios. Such losses should also be considered in designing improved nutrient management practices to minimize unwanted environmental impacts of different cropping systems.

In modelling studies of this nature, it is important that all important processes are represented accurately (Keating et al., 2001). Two major uncertainties in this study were N and P mineralization rates in the soil and soil sorption of P, both of which could have influenced leaching losses. Unfortunately 1-D modelling does not account for the added effects of irrigation systems with low uniformity on N and P leaching from cropping systems. Furthermore, any potential preferential flow that may have occurred in the wetter irrigated profile was not simulated. Nonetheless, this study shows that long-term modelling can be used to provide insights into N and P dynamics in cropping systems, and the suitability of different mitigation measures in reducing N and P leaching losses. Modelling work of this nature can also be done in conjunction with field measurements and to plan field trials more effectively.

## 7.5 CONCLUSIONS

Deterioration of water quality as a result of N and P export from cropping systems requires innovative management practices at the local scale to reduce this type of non-point source (NPS) pollution. As N and P leaching losses from cropping systems are difficult to measure and monitor, the use of long-term modelling can effectively improve understanding on N and P export, as demonstrated in this study.

SWB-Sci was successfully used to compare N and P leaching losses for four different management scenarios. Maize under irrigation was shown to leach far greater loads of N and P compared to dryland maize production. Using a 'room for rain' strategy reduced N and P leaching relative to a standard irrigation scheduling system, but the effectiveness of the strategy varied between seasons. Including a wheat crop over the winter season also reduced N and P leaching, despite increased rates of irrigation and fertilization.

The continued use of models such as SWB-Sci to conduct long-term simulations to analyse critical N and P leaching periods for different cropping systems is recommended. This will lead to the identification of effective management practices to reduce these losses. In addition, modelling can also assist in the planning of field trials and monitoring programmes to further enhance our understanding of these issues. Finally, further research is needed on the optimal management of deep drainage to remove unwanted salts while minimizing the losses of valuable plant nutrients, and here too modelling has an important role to play.

## 7.6 ACKNOWLEDGEMENTS

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# CHAPTER 8
# CONCLUSIONS AND RECOMMENDATIONS

## 8.1 OVERVIEW OF STUDY

Nitrogen (N) and phosphorus (P) leaching losses from the rootzone of cropping systems can lead to deterioration of fresh water quality and represents an economic loss to farmers. Quantification of these leaching losses requires accurate estimation of deep drainage and the N and P concentrations in this deep drainage, but these two variables are difficult to measure. For this reason modelling is often used to estimate N and P fluxes from the rootzone. This study was done improve understanding of the leaching losses of these two nutrients and encompassed the development, testing and application of a modelling tool that could effectively be used to analyse leaching losses at the local scale. Following the inclusion of N and P subroutines into the locally developed SWB-Sci model, initial testing was done using three historical datasets and data collected from a drainage lysimeter trial as part of this study. Long-term simulations were then used to compare N and P leaching losses for dryland versus irrigated agriculture and to explore the effect of best management practices on reducing N and P leaching losses.

## 8.2 GENERAL CONCLUSIONS AND RECOMMENDATIONS FOR MODELLING N AND P AT THE LOCAL SCALE

Nitrogen and P simulating capabilities have now been successfully incorporated into the SWB-Sci model (see Chapter 2). Although algorithms were primarily obtained from existing models, this exercise provided an excellent learning opportunity on N and P dynamics in cropping systems and the different approaches used to model these dynamics. The existence of a range of similar models worldwide is acknowledged, but having the ability to edit and modify source code allows greater flexibility when simulating a diverse range of cropping systems and for long-term modelling exercises. Considerable de-bugging and testing was required following the inclusion of N and P algorithms. During the development phase and the design of interface screens, achieving high user-friendliness in the model was a priority. It is expected that the SWB-Sci model will continue to undergo refinement and be widely used by researchers in the future, building on the large amount of work that has already been done on the simulation of the soil water balance, crop growth, and salt dynamics. The highly mechanistic approach, the generic way in which crop growth is simulated, and the ability to simulate a wide range of morphologically different crops favours the wide applicability of this model.

Early on during this study it was realised that obtaining the soil parameters required to model P for South African soils is not a straightforward exercise. It is anticipated that soil parameterization work and the guidelines developed as part of this research will increase the effort directed to P measurement and modelling in South Africa to further reduce loss of P from cropping systems and minimise unwanted impacts of NPS pollution (see Chapter 3). Further work is needed to test the general applicability of the equations used to estimate the quantity of *Labile P* and the P availability index (PAI) of local soils. A follow-on study is currently underway to improve understanding of the soil characteristics important in determining P sorption in soils (Du Preez – personal communication), and it is envisaged that this work will assist in further improving the algorithms used to model P interactions with the soil matrix. The appropriateness of the guidelines provided in this thesis to categorize South African soil forms as calcareous, slightly weathered or highly weathered also requires further development. A lack of suitable P data collected locally and across scales is still a limitation in testing these algorithms and guidelines. New monitoring to collect this type of data and the continuation of existing monitoring is therefore recommended to improve our ability to better manage P.

During model testing exercises with the N datasets from the Netherlands and South Africa, the model performed well in simulating N dynamics in cropping systems (see Chapter 4). The new approach to simulate the effect of N stress on yield on a daily basis following flowering, as opposed to simulating the effect of N stress on the harvest index as used in CropSyst, proved to be effective. As also observed by De Willigen (1991), aboveground N variables were more accurately simulated than belowground N variables. For both the South African and Netherlands datasets, correlation between measured and simulated soil inorganic N levels were not evaluated according to statistical criteria as was the case for other variables. This was because low overall correlations, most likely due to high soil variability, make these prescribed statistical criteria too stringent. In some cases, added fertilizer N was observed to 'disappear' in the measured data, adding to the difficulty in trying to compare measured and simulated values. Nonetheless, simulated changes in soil inorganic N levels and trends over the growth season were often similar to measured values. In simulating soil organic matter in soils, the model requires that users input the size of the different fractions making up the soil organic matter (SOM), including the 'microbial biomass', 'active labile SOM', 'active meta-stable SOM' and 'passive SOM', at different soil depths. These fractions influence mineralization and immobilization rates significantly, so it is important that they are accurately represented for the particular soils being simulated. Freshly mineralized inorganic N is clearly an important contribution to crop available N (see Chapter 4), and development of a simple laboratory procedure to assist users to obtain these values could be highly beneficial. It is also suggested that the model be modified to simulate the influences of the stony fraction in soils on organic matter mineralization, soil water movement and other relevant processes in order to improve overall accuracy.

New algorithms to simulate crop P demand and uptake, P stress effects on crop growth, and banded P fertilizer applications were included into SWB-Sci (see Chapter 5). During testing exercises using a dryland maize dataset collected in Kenya, the model was observed to simulate aboveground dry matter production (TDM), yield, leaf area index (LAI), profile water content, aboveground N and P mass and grain N and P mass with varying levels of accuracy. Unfortunately soil N and P levels were not measured in this trial so this made testing and comparison of measured and simulated values more difficult. Except for aboveground P mass, agreement between measured and simulated values was almost always better for the first growth season (SR89) than for the second growth season (LR90). Exact reasons for poorer performance by the model during the second season are not immediately clear. There could have been something that happened in the field when transitioning from the one season to the next that is not adequately captured in the simulations, or some of the newly developed algorithms still need further improvement, so further testing and refinement of these newly included algorithms is recommended.

Similar research on the critical assessment of a model to mechanistically estimate the effects of both N and P stress on crop growth, and to statistically evaluate model performance using a wide range of variables including TDM, yield, LAI, profile water content, aboveground N and P mass and grain N and P mass, could not be identified in the literature. Work done in this thesis therefore contributes significantly to the future inclusion of the simulation of P stress effects on crop growth to the great amount of mechanistic, local scale N modelling that is carried out. Good datasets for testing mechanistic P models are still lacking. Field trials involving the extensive measurement of crop P uptake, soil P and runoff and P leaching losses are required to improve our ability to study P dynamics and further progress our ability to simulate P at the local scale.

During the testing exercises discussed above, several areas where further research and the inclusion of additional processes could help improve the model were identified. Work on the effects of N and/or P stress on leaf development and crop LAI for different crops is recommended. The incorporation of a special stress factor that accounts for P stress on LAI, as exists for N, should be considered. These improvements would potentially lead to better estimation of crop water use. In addition to the crops maize, wheat and swiss chard modelled as part of this research, testing the model with other crops, especially with regards to P uptake, is recommended to more fully explore the generic applicability of the SWB-Sci model. It is also proposed that the model be further adapted to simulate N and P dynamics under drip and micro-irrigation as these two forms of irrigation are gaining in popularity as methods to irrigate more efficiently world wide.

Although runoff losses of soluble N and P are simulated in the model, the leaching focus of this research meant that the runoff algorithms were not tested. Further testing of these algorithms, and the incorporation of routines to simulate erosion, which will enable N and P sediment loss estimations, is recommended for SWB-Sci. In the application of the model, it is always essential for users to fully understand what they want to accomplish with a model (Sharpley, 2007), and further knowledge of the strengths and weaknesses of the model will assist with this. A comprehensive, up-to-date user's manual incorporating the crop, soil, weather, salt and nutrient units is recommended to assist future users in the practical application of the model.

## 8.3 MONITORING AND MODELLING MOBILE AND IMMOBILE SOIL WATER PHASE SOLUTE CONCENTRATIONS

The accurate estimation of solute leaching from agro-ecosystems is highly important in maintaining fresh water quality, but suitable and universally applied techniques to estimate drainage fluxes and solute concentrations in these drainage fluxes are lacking. A drainage lysimeter trial was used to more closely evaluate our ability to simulate vertical solute movement in soils, focusing on the role of mobile and immobile soil water phase $NO_3^-$ and P concentrations (see Chapter 6). As hypothesized, WFD $NO_3^-$ and P concentrations were observed to align closely with simulated mobile phase concentrations, and SC $NO_3^-$ concentrations were observed to align closely with simulated immobile phase concentrations. These results highlight the potential for the use of measuring and modelling together to estimate leaching. Two approaches are possible. The first involves using measurements to calibrate the model and test long-term model accuracy. The second involves measuring solute concentrations with active and/or passive samplers, and modelling to estimate drainage fluxes only, and using these values together to estimate leaching. In both these approaches, WFD and SC data can be valuable in assisting users to estimate the drainage factor, drainage rate (mm $d^{-1}$) and solute mixing factor for the soil. Additional research, encompassing studies done on a wide range of soils and for cropping systems with varying fertilization and irrigation management practices is needed to test and develop this approach further. Nonetheless, the suggestion provided here is meant as a pragmatic approach to enable the immediate estimation of N and P leaching in critical areas where no similar, simple to implement approaches have been adopted.

Although a wide range of approaches have been developed to model solute movement in soils, instances when these algorithms were tested by someone other than the developer are rare (Addiscott and Wagenet, 1985). It is hoped that the ability of SWB-Sci to simulate N and P dynamics, especially in the mobile and immobile soil water phases, will be further investigated by other researchers for a wide range of soils. The approach used to model incomplete solute mixing is relatively simple, and should be considered for inclusion into larger scale models such as ACRU-NPS.

Finally, SCs, WFDs and modelling can also be used effectively to address and manage salinity issues in the rootzone and NPS salt pollution from cropping systems, and further work is needed to assess nutrient and salinity management together to reduce the overall negative impact of cropping systems on the environment.

## 8.4 LONG-TERM SIMULATIONS TO INVESTIGATE N AND P LEACHING LOSSES FROM CROPPING SYSTEMS

Long-term modelling with SWB-Sci was successfully used to study N and P leaching from different cropping systems (see Chapter 7). In such an approach, validity depends on the assumption that historical climate data is a guide to future climate data, and that the model provides a realistic representation of the biophysical processes (Keating et al., 2001). Although a model such as SWB-Sci cannot be 'validated' in the sense that it can provide unequivocally accurate simulations (Keating et al., 2001), confidence in a model is generated through extensive testing.

Using 30 year simulations, monoculture maize production under irrigation was observed to leach higher loads of N and P from the profile compared to a similar dryland production system. On numerous occasions, zero leaching losses were observed over multiple consecutive years for the dryland scenario. Application of a 'room for rain' irrigation strategy was observed to reduce N leaching by 12% and P leaching by 14%. A crop rotation system was even more effective, reducing N leaching losses by 23% and P leaching losses by 24%, despite the application of much higher amounts of irrigation water and fertilizer.

Nitrogen and P leaching losses were clearly event-driven, and amounts leached often varied widely between seasons. For this reason, long-term modelling is crucial in assessing and comparing the long-term effectives of different BMPs. Long-term modelling can also be used to guide planning and monitoring approaches when designing field trials.

## 8.5 BEST MANAGEMENT PRACTICES (BMPs)

With increasing environmental pressures on farmers, and rising fertilizer and production costs, current farming practices will need to shift towards more environmentally and economically sustainable management strategies. An ability to accurately estimate N and P leaching losses in different cropping systems is essential for the identification of suitable BMPs. Existing agronomic guidelines often do not adequately consider environmental implications; for example, soil P test recommendations are based on crop responses and not environmental risks such as runoff P enrichment potential (Sims and Sharpley, 1998). Several BMPs were investigated in this study. In the drainage lysimeter trial, using WFDs to guide irrigation was judged to be successful as drainage from the bottom of the profile was only caused by rainfall later in the season (see Chapter 6). Having WFDs buried at 45 and 60 cm served to ensure that over-irrigation was not occurring. Applying N fertilizer to the swiss chard crop only when $NO_3^-$ concentrations measured from the WFDs located in the root zone was below 100 mg $l^{-1}$ was not assessed to be completely successful in reducing N leaching from the profile. Accounting for N that is available to the crop deeper in the soil is also clearly important, and high N leaching from the profile could potentially have been reduced by not applying subsequent N fertilizer, forcing the crop to remove N from deeper in the soil profile. This may have made negative effects on yield and could represent a trade-off between economics and the environment.

In the long-term modelling study, a ‘room for rain’ irrigation scheduling strategy and a crop rotation strategy were found to reduce N and P leaching losses, with the crop rotation strategy proving more effective (see Chapter 7). Future work exploring BMPs at the local scale could include analysing the effect of fertilizer application timing, applying smaller amounts of fertilizer at a time in the irrigation water (fertigation), application of fertilizer with different rates of availability, more efficient irrigation systems and scheduling practices. It is also recommended that similar scenarios be investigated for cropping systems in different climatic zones in South Africa, especially for intensive horticultural crop production. In addition to this, the role of soil depth in N and P leaching is also recommended for further investigation. In such work identifying 'leaky' cropping systems and exploring appropriate BMPs, economists clearly have a major role to play in assessing feasibility.

In its current form, SWB-Sci can be used as a research tool to address many of the abovementioned issues and thereby play an important role in reducing N and P leaching from agricultural systems to fresh water systems.

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## SUMMARY

Nitrogen (N) and phosphorus (P) leaching from croplands to fresh water systems can lead to eutrophication and deterioration in water quality. Intensification of agricultural practices and extending cultivated areas to feed a growing population makes this type of non-point source pollution a growing concern. As leaching losses are highly challenging to monitor and quantify, modelling is becoming increasingly important as a tool to improve our ability to estimate N and P leaching losses. Such modelling is carried out at different scales, ranging from the local scale to represent a single field, to the larger catchment scales which account for the both the sources of these pollutants as well as the hydrological pathways to the receiving water bodies. Modelling at the local scale is often most effective in addressing the impacts of different water and crop management practices on N and P leaching, and is the scale focused on in this study.

In order to improve our ability to understand and manage N and P leaching, subroutines to simulate these two nutrients were included into the locally developed, local scale SWB-Sci crop model. In some cases existing algorithms were modified or new approaches developed as required. Most notably, new approaches to simulate N stress effects on yield; crop P demand, uptake and stress effects on crop growth; banded P fertilization applications; and incomplete solute mixing in soil water were included into the model. The decision to build N and P simulating capabilities into SWB-Sci was taken despite the existence of similar models primarily because of the flexibility and increased capacity that having an in-house model provides in simulating a diverse range of cropping systems and testing fine scale processes.

Following development and debugging, the ability of the model to simulate N and P dynamics in cropping systems was tested using several historical datasets from the Netherlands, Kenya and South Africa, as well as a dataset collected as part of this research. Variables tested included total aboveground dry matter production, yield, leaf area index, profile water content, aboveground N and P mass, grain N and P mass, and soil inorganic N content. Measured and simulated values were subjected to statistical analyses in order to assess model performance in all cases except for soil inorganic N. The model was observed to simulate the various variables tested with a

range of accuracy, and in almost all cases, the model simulated the effect of nutrient stress on crop growth well. Although the new model was judged to be robust, continued testing of the various processes and refinement of approaches and algorithms is recommended to improve the model further.

A drainage lysimeter installed with wetting front detectors and suction cups was used to study vertical solute movement more closely. Previous research has shown that estimating solute concentrations in the mobile soil water phase is important when modelling leaching losses. As wetting front detectors are able to collect a water sample from a wetting front (0 to -3 kPa) and suction cups are able to collect a sample from the immobile or resident soil water (-60 to -70 kPa), it was hypothesized that nitrate ($NO_3^-$) concentrations measured in wetting front detectors and suction cups would align with simulated $NO_3^-$ concentrations in the mobile and immobile soil water phases, respectively, and this was observed through experimentation. Phosphorus concentrations measured in the wetting front detectors and those simulated in the mobile soil water phase were also observed to align, but not as closely as for $NO_3^-$. These results demonstrate the value of measuring and modelling together to provide more accurate estimates of solute leaching from the rootzone. Additional research, including studies using a wide range of soils and irrigation and fertilization techniques is recommended to develop this approach further. From this trial, high potential was also observed in the use of wetting front detectors and suctions cups in guiding irrigation and fertilization management practices.

Long-term (30 year) modelling with SWB-Sci was used effectively to analyse and compare N and P leaching losses from dryland and irrigated cropping systems. An irrigated maize monoculture system was simulated to export higher N and P leaching loads compared to dryland production, with N leaching being 480% higher and P leaching being 420% higher. For the irrigated monoculture maize system, irrigating to maintain 30 mm ‘room for rain’ in the soil profile reduced N leaching by 12% and P leaching by 14% over the 30 year simulation period. A crop rotation system, which incorporated irrigated wheat in the winter months, resulted in an even greater reduction in leaching losses despite higher overall applications of N and P fertilizer and irrigation water. Compared to the irrigated monoculture maize scenario, the crop rotation systems led to a 23% decrease in N leaching and a 24% decrease in P

leaching. Nitrogen and P leaching losses were usually associated with large rainfall events and often varied widely between seasons. Long-term modelling was therefore confirmed as an important tool in analysing N and P leaching losses, designing field trials and monitoring experiments, and exploring appropriate best management practices.

As a result of this study, it is strongly envisaged that enhanced understanding of N and P dynamics in cropping systems, and the use of SWB-Sci as a tool to increase our understanding further, will lead to the reduction of N and P leaching losses through improved management practices.