Investigating interactions between biophysical functioning, usage patterns, and livelihoods

in a wetland agro-ecosystem of the Sand River Catchment through dynamic modeling

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Executive summary

A large amount of work – both developmental and research-based in nature has been undertaken in the Craigieburn wetland of South Africa, a system which is severely degraded. The early findings indicated that an intimate relationship between land-use practices, erosion (within a naturally eroding landscape), and a reduction in the water table. Certain land use practices in the wetlands exacerbated this. The declining soil moisture, compounded by certain management practices, resulted in a loss of fertility and hence agricultural production. It was found that the poor state of the wetlands and surrounding micro-catchment is primarily due to the lack of soil and water conservation practices and poorly conserved fields, poor veld condition, a high density of homesteads, lack of water harvesting mechanisms and an extensive path and track network. The lack of adequate vegetational cover results in high water velocities, which combined with the soil properties, and the presence of numerous footpaths which concentrate runoff, contributes to the observed erosion (sheet deposits, rills and gullies). This state leads to decreased infiltration and an augmentation of peak discharges, exposing the wetland to greater risks from erosion. Farmer practices within the wetlands have acted to increase water velocities and bed erosion, and reduce organic matter.

The key **negative impacts** on the state of health of the wetland of the combined on-site and catchment activities have been:

- Increased levels of sediment loss from the hillslopes and deposition within the wetlands have acted to further 'oversteepen' the wetlands and increase susceptibility to headcut erosion;
- Desiccation of the wetland;
- Increased levels of organic matter and nutrient losses from the system.

Importantly, declining wetland health is expressed in declining crop yields (mainly of *colocasia esculenta*, the most ubiquitously grown wetland crop). This decline has implications for peoples' livelihoods (see Figure 12) who are for the most part, extremely poor elderly women.

In response a farmer support programme was initiated in 2005. This involves collaboration with farmers on understanding and potentially modifying deleterious landuse practices as well as support for those that are beneficial.

Given that it is neither feasible nor ethical to seek change in farmer practices without some level of certainty regarding the outcomes, we sought to examine the impacts of change through modeling. The large amount of existing information for the wetland area supported such an approach.

Thus, the objective of this project is

> to harness existing knowledge and to formalize the relationships and interactions between the biophysical sphere and the users' practices, into a meaningful, integrated representation of the situation in the wetlands under different landuse practices in order to investigate the associated risks incurred, their magnitude and occurrence patterns, and ultimately the effects on users' livelihoods and welfare.

Such research requires an integrated and systemic approach since many different elements and processes enter into interactions. Furthermore, certain actions or processes differ in dynamics, timing and duration (e.g. typically cropping systems and practices, climatic and hydrological events). Also, some of these dynamics form sub-systems on their own, including inner processes and dynamics. Such complexity and dynamics lend themselves to dynamic modeling. The Stella platform was chosen for this purpose.

Recognizing the limited quantitative information available on some of the complex and integrated processes, an important secondary objective of the modeling is one of understanding and learning with a particular focus on gaps in knowledge.

A number of questions guided the model design. These focused on exploring the impacts of different landuse practices on wetland health and livelihoods. For practical purposes, these changes in practices were then grouped and used to generate scenarios. The key questions were as follows.

Overall field management on wetland health

1. What impact is resting likely to have on wetland health?

Bed design

1. What is the impact that each of the following is likely to have on wetland health:
   - Re-orientation of beds
   - Blocking of furrows
   - Staggering of beds to reduce water velocity.

Bed preparation

1. What impact is the use of minimum **tillage techniques**- currently being supported through the farmer support programme - likely to have on wetland health?
2. What impact is **mulching** and/or live cover – thought to be considerable - likely to have on wetland health?
3. What impact is increased **manure** application, employing conservation tillage techniques, likely to have on wetland health?
4. What impact is not **burning** likely to have on wetland health? (It is assumed that if farmers stop burning cleared vegetation, this will be available for mulching).

Overall micro-catchment management

1. What impact does a major rainfall event have?

An important finding for future work is the recognition that despite the substantial body of work that exists for Craigieburn wetland, there still exists a dearth of data of the type needed for meaningful input to dynamic modeling. Thus for example, an initial SOM value was set at 3% which was based on values from elsewhere rather than field measurements. although linkages had been established by earlier research, (see for example Figure 8), little is known about the **relationships** between these variables. Thus for example, whilst SOM affects soil structure, as shown in the same figure, the nature of this relationship is not described and had to be estimated.

The following preliminary conclusions can be drawn from the modeling exercise.

- The most significant impact on erosion (i.e. reduction in erosion) and water stress appears to be achieved through mulching, and crop/vegetational cover, and to a lesser extent through the application of manure.
- Unsurprisingly, erosion increases markedly when the clearing of land is syncrohnised with rainfall events (such as in November). This includes clearing due to weeding – an important issue to be considered by the *farmers support programme*. In other words, if weeding is not combined with mulching, the disadvantages (extremely high erosion) far outweigh the benefits of weeding.
- What is less clear from the above results are the impacts of changed bed management (i.e. bed and furrow orientation and the blocking of furrows). This is thought to reflect limits to the model and is further addressed in the discussion.
- Improvements in fertility and production are seen with the application of manure (4 kg/m^2), resting and mulching. However, the initial application of higher levels initially (4 kg/m^2) than those that are currently reported in Craigieburn appears to be quite important.
- Thus overall, it appears that based on our current understanding of relationships in Craigieburn wetlands, the application of manure, attention to mulching and resting of land – if possible – are likely to have the biggest positive impacts.

- Unsurprisingly, taking the field out of production for the 4-year period has a strong mitigatory effect. However, in the absence of any other measure resting land certain years may have a very positive effect on soil restoration, and maintaining following yields at good levels.

An important aspect of this work was to improve **integration** across disciplines (biophysical, social and economic data) so as to arrive at a meaningful – if incomplete – picture of the Craigieburn wetland. The process of constructing a collaborative 'straw-dog' model through Stella was well-received amongst specialist. It encouraged specialist thought and discussion beyond individual fields of expertise and encouraged making linkages so as to develop a more holistic interpretation of reality. It also served to highlight essential research required to build a more complete snapshot of reality. Since learning and identification of knowledge gaps was an objective of this exercise, this has been achieved and further research is underway.

The lack of a spatially explicit model together with limited data made a holistic examination of the wetland micro-catchment very difficult. This would for example allow for an examination of the contributions from hillslopes (water, sediment, nutrients) and neighbouring wetland zones. This is important because wetland health – as defined in this work – is predicated on the soil and water balance (inflow and outflow).

Acknowledgements

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PART A
INTRODUCTION AND BACKGROUND

1. Introduction and background to the research

This project forms part of the CP30 Programme and reflects work being undertaken on wetlands and livelihoods in the Sand River Catchment. This catchment lies in the north-eastern region of South Africa and falls within the Inomati Water Management Area. This catchment, with some of South Africa's poorest rural populations, some of its most pressing environmental degradation, and some of its most misguided development activities, has been the focus of integrative planning and action towards holistic environmental management. This initiative, known as the Save the Sand Programme (SSP), is a pilot project for Integrated Catchment Management in South Africa which seeks to address the rehabilitation of the Sand River and its tributaries in a holistic manner through effective and integrated catchment management. The wetlands initiative, known as the 'Wetlands health and livelihoods security' project, part of which is reported herein, comprises part of this programme.

The SSP arose because, as a socio-ecological system, the Sand Catchment is severely degraded (Pollard *et al.* 1998; Biggs et al. 2007). This reflects many factors which are elaborated in Section 2. Notably, the area carries - and will continue to carry - the legacy of apartheid. Under the policy of 'separate development', the area become one of the bantustans into which black people where forced removed. Recent studies by Pollard, et al. (2005) have demonstrated that the population of the area rose dramatically – by 1000% - between 1970 and 1990. Today some 383,000 people live in the area resulting in a population density in some areas that equals that of the Netherlands (350 p/km^2). Part of this legacy is that like all former Bantustans, poverty and other attendant social problems are prevalent. Not surprisingly, this extraordinary increase in population densities over such a short period has put considerable pressure on the areas natural resources as people attempted to survive.

In terms of biophysical attributes, water is the most limited and limiting renewable resource in the catchment. The historically perennial Sand River now ceases to flow downstream of the mid-region in dry years. This is despite the government's commitment to meeting the needs for environmental flows. The main cause of flow modification is the state-owned commercial agricultural schemes in the middle reaches and, to a lesser degree, the commercial forestry in the upper reaches. The forestry is now being removed under a negotiated land-use change, initiated by the SSP. Other natural resources such as wetlands and woodlands are also under threat. A major outcome over environmental degradation is the impacts on peoples' already vulnerable livelihoods, trough the loss of ecosystems goods and service. The consequences are highest for the poor whose DIRECT dependence on natural resources is highest.

The wetlands of the upper Sand River lie in communal areas and play an important role, both in terms of local-catchment water security and the livelihoods of local people. Indeed, the 'wetland health and livelihood security' project was initiated partly in response to an approach by wetland users who requested support in addressing wetland degradation. Initial visits to the Craigieburn wetland also suggested that most of the farmers were women, often constituting the poorest of the poor. Loss of wetland integrity therefore potentially exacerbated their already precarious livelihoods. An integrated approach that addressed both biophysical and social aspects was deemed to be an appropriate way forward. Moreover, research was necessary in order to understand the underlying causes and their effects and ultimate impacts.

In response, the SSP undertook a research project designed to provide the necessary biophysical and social information needed to develop an integrated rehabilitation and management plan (Phase I). The project focused on the wetlands used by Craigieburn village in the north-western region of the catchment, where the wetlands are used mainly for small-scale agriculture and to a lesser extent, for reed harvesting (Figure 1). These data and empirical observation by experts suggest that there is a strong link between some key biophysical features and evolution of the wetlands on the one hand, and the usage and the management of agrosystems on the other hand. This in turn has impacts for wetland health and to users' livelihoods and welfare (see below).

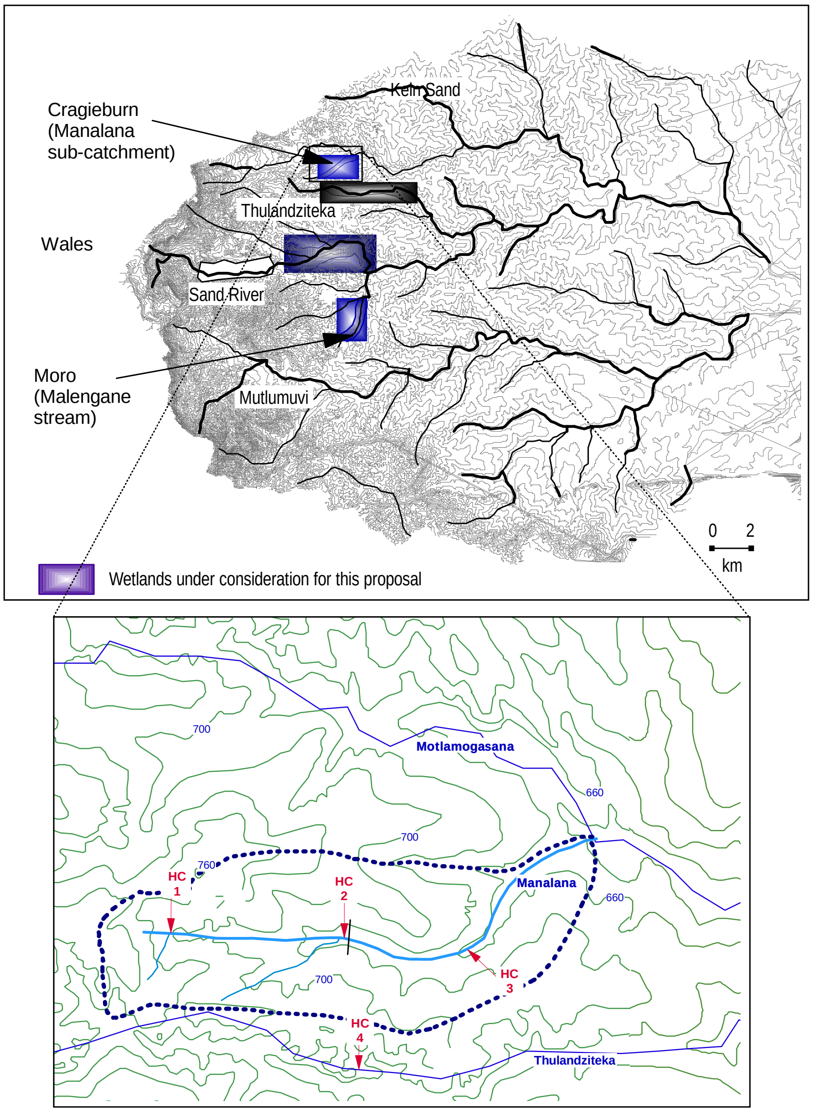

Figure 1 (a) The upper Sand River Catchment; (b) topographical detail of the chosen study site- the Manalana sub-catchment and the location of erosion headcuts

A number of issues that arose from the first phase are collectively being addressed as part of Phase II (see site description). These include: (1) the need for technical rehabilitation of three large headcuts which threaten these wetlands; (2) the need for awareness-raising, linked to (3) changing practices of the wetland users, in particular the subsistence farmers and, (4) the need for community-based governance of these wetland areas (Pollard *et al.* 2005).

By working with the wetland users through a *farmer support programme*, the aim is to address negative practices and impacts occurring directly within the wetland (started January 2005). However sufficient is known about human behaviour to know that change is slow and that it is unlikely that farmers will be willing - or able - to change all their practices of wetland use. Change is a process rather than a once-off product and is best achieved through sustained efforts. Moreover, the effects of changed practice – such as an improvement in fertility - are only likely to be seen over a longer time scale than one growing season.

This report is structured as follows. Part A provides the background to the modeling. In Section 2, the reader is introduced to the objectives of the project and a summary of the overall approach. This is followed by a synopsis of findings (Section 3) from previous research in the wetlands, since this is used in the modeling. This is supported by a brief literature review (Section 4). Part B details the application, results and conclusions of the dynamic modeling exercise.

2. Research questions and an introduction to the overall approach: Why dynamic modeling?

Given this backdrop, questions arose as to the impacts of the landuse practices on wetland health and which of the practices were having the greatest negative or positive impacts? If certain practices changed what would the impacts be on wetland health and thus livelihoods? Also, given that not all practices are likely to change, which would be key to addressing wetland health? In order to answer these questions, given that experimenting with vulnerable peoples livelihoods is neither ethical nor practical, we decided that computer modeling of potential impacts was more appropriate. To do this a dynamic modeling project was initiated in partnership with the University of Pretoria (based on a Stella platform).

Thus the objective of this project is:

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Such research requires an integrated and systemic approach since many different elements and processes enter into interactions. Furthermore, certain actions or processes differ in dynamics, timing and duration (e.g. typically cropping systems and practices, climatic and hydrological events). Also, some of these dynamics form sub-systems on their own, including inner processes and dynamics (e.g. typically soils, natural vegetation). Such complexity and dynamics lend themselves to dynamic modeling.
Dynamic modeling helps one to understand the dynamics and complexity of real-world processes by mimicking (with a computer) the actual but simplified forces that are assumed to result in a system's behavior (Ford 1999; Hannon and Ruth 2001). The models created can indeed predict certain evolutions, but this research intends rather to:

a) experiment and demonstrate the effect of certain usages and practices on wetlands,
b) highlight certain interactions, and also to
c) stimulate further research on specific sub-systems or processes that remain largely unknown, or poorly documented in the local research context (Deaton and Winebrake 2000; Ford 1999).
d) Finally, the model may be used to generate awareness at the local level regarding the potential risks incurred by certain practices.

Recognizing the limited quantitative information available on some of the complex and integrated processes, an important secondary objective of the modeling is one of understanding and learning with a particular focus on gaps in knowledge.

Despite these objectives, it must be noted that working through models does not intend to solve - definitively - issues of economic or social optimality, or of sustainability of land use and wetland conservation.

The Stella®[1] modeling environment was used for the research. The model focuses on the dynamics of ridged beds under various cropping practices, the interactions with local hydrological factors (i.e. in the riverine wetland agro-ecosystem) and investigates the linkages between these two and the users' livelihoods and welfare. Stella has been used similar exercises to improve ones understanding of the linkages within and between social and ecological systems (see for example Eppink, et al. 2004; Chopra and Adhikari 2004).

3. Study site and findings from previous work

3.1 The Sand River Catchment as a case study area

Craigieburn is a headwater wetland of about 140 ha that receives the bulk of its water from runoff and groundwater in the rainy season, and via groundwater input in the dry season. It is located in the north-eastern region of the Sand River Catchment (see Figure 1). The Sand River Catchment is a relatively small area of 2000 km^2 and home to some 383,000 people (Pollard et al. 1998). With the exception of the wetter, western mountainous region, the catchment is semi-arid with an average rainfall of 600 mm. The Sand River rises at an altitude of some 1800 m but descends rapidly to an altitude of 500 m in the lowlands (known in South Africa as the lowveld).

Data from the Wales rainfall gauge (Station no: 594819; $30^o58'$; $24^o39'$; 10904 – 2004 daily, patched) records an average rainfall of 1084 mm. This is however highly variable. Rainfall is strongly seasonal falling between October and March (Figure 2).

The average mean annual summer temperatures range between 26 – 31^o C, and rarely drop below 10^o C in winter (Schulze and Maharaj, 2004).

The area comprises principally the former Bantustans of Gazankulu and Lebowa. Over the years, livelihoods for the catchment residents became increasingly vulnerable under grand apartheid planning (Pollard *et al.* 2007) and today, most families rely on income from pensions or wage remittances. The effect of poverty that accompanied mass removal of people to the area is reflected in the increasing environmental degradation.

[1] www.isee.com, and Hannon & Ruth (1994)

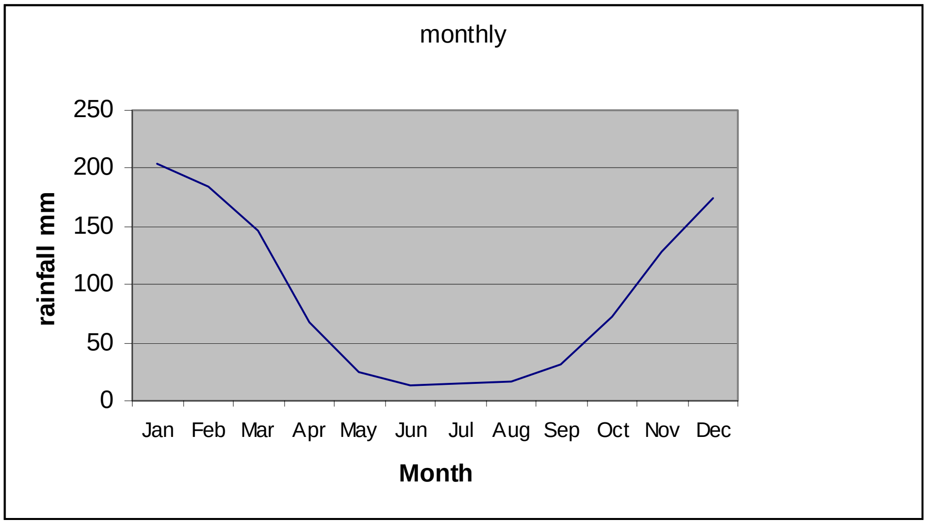


Figure 2 Average monthly rainfall data for Craigieburn (Source: Wales rainfall station)

The main land-uses (Figure 1) include commercial forestry in the upper catchment, rural residential areas combined with subsistence agriculture, and some limited irrigated agriculture in the central region, and conservation (mainly exclusive high-income tourism) in the eastern region.

3.2 Craigieburn wetlands: Summary of findings from previous work

The wetland farmers who approached AWARD for support in addressing wetland degradation cited desiccation, erosion and reduced fertility as key concerns. The baseline research (Phase I) established the relationship between these factors and demonstrated that indeed wetland integrity was being severely compromised by both within-wetland practices, as well as by landuse practices in the surrounding micro-catchment. In summary, an intimate relationship exists between landuse practices, infiltration - and runoff - and erosion, and between erosion and a reduction in the water table. Landscape desiccation reflects a change in these relationships as described below.

A series of interlinked factors lie behind this. Some of these are related to the inherent biophysical characteristics of the area (sandy soils) whilst others reflect current landuse practices in the area. For example, farmers are drawn to the wetlands because of moist conditions but then subsequently drain them through canals and raised beds, citing water-logging as a problem.

First however, it is instructive to appreciate landcover/ landuse changes that have occurred. This information was calculated from aerial photographs. The micro-catchment area of the wetlands under consideration is approximately 140 ha (Table 1). The effects of moving people into the area are highly visible between 1965 and 1974 when the residential areas increased dramatically and veld areas decreased (Figure 3). Wetlands are estimated to have decreased by 50% (as suggested by the vegetation/ soil data comparison) from 23 ha to about 13 ha.

Table 1
Landcover/ landuse in the Craigieburn micro-catchment over the past 50 years. Wetland areas were estimated from a combination of 'reeds' + 'mixed plots' (from Pollard et al. 2005). This data is taken from aerial photographs

	AREAS (M^2)						
Year	Veld	Residential	Maize	Reeds	Dongas (erosion feature)	Mixed plots	TOTAL
1954	1,114,337	46,800	5,584.8	223,277.8	10,000	10,000	1,400,000
1965	1,064,064	36,000	8,213.1	281,722.5	10,000	10,000	1,400,000
1974	652,163	484,200	14,607.8	213,114.6	10,000	25,915	1,400,000
1984	803,184	383,400	16,552.5	172,514.8	10,000	14,348	1,400,000
1997	887,664	352,800	15,535.3	120,380.2	10,000	13,621	1,400,000

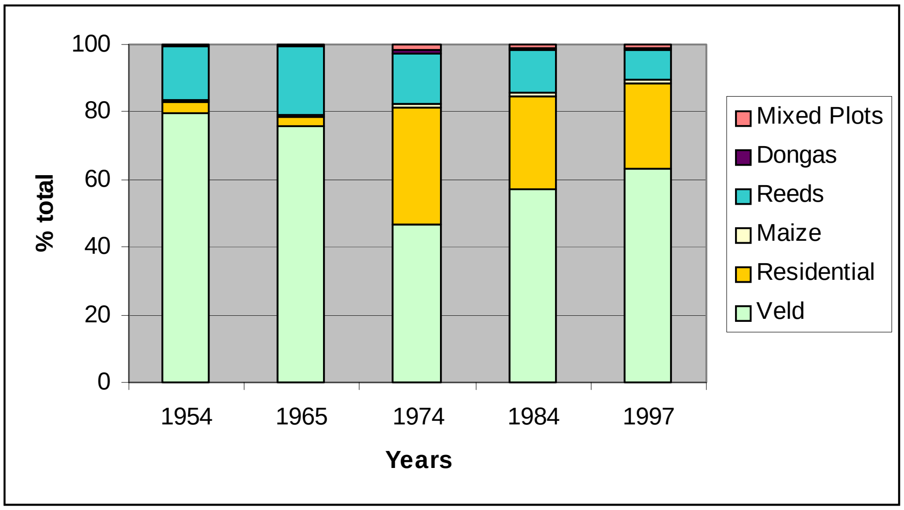


Figure 3 Changes in landuse between 1954 and 1997

Major threats to Craigieburn wetlands and peoples' livelihoods

Erosion is the major threat to the wetlands of Craigieburn and hence to peoples' livelihoods. Studies undertaken in 2003/2004 suggest that the desiccation of the wetlands and the surrounding landscape is intimately linked to erosion. This in turn impacts on production (see later). Erosion is caused by a number of factors. First, at a geological scale, the wetlands occur in an area a naturally eroding landscape. This is borne out by an assessment of aerial photographs dating back to 1937 in which population densities are extremely low but existing erosion features such as dongas are widely evident (Pollard et al. 2005).

Secondly, clearing of the hillslopes that surround the wetlands has provided diffuse sediment source into the wetlands. In Craigieburn the main impact, which is acute, is on the slope as the wetlands accumulate sediment. This aggregated sediment is very difficult to remove and the only way is through incision- the effect of which are profound (see later). Finally certain farmer practices within the wetlands - elaborated below – act to increase water velocity and hence erosion.

Thus it is important for the purposes of this report to differentiate two 'types' of erosion.

- The last point above discussed what we term 'within-wetland erosion' where sheet or rill erosion is evident of the surface of the wetland plots (Figure 4a).

- A more visible and acute type of erosion is that referred to as 'headcut erosion' which describes erosional features that advance upstream through a wetland, effectively causing a major loss of wetland extent (Figure 4b). At a **macro-scale**, Craigieburn wetlands occur in "oversteepened" sections (Figure 4) where the water table is held in place by a plug of fine material at the toe of the wetland. This landscape setting means that Craigieburn wetland is highly vulnerable to erosion as landscape processes seek to reduce the wetland slope, as shown in Figure 5). The gulley erosion and loss of fines at the toe of the wetlands raises the hydraulic conductivity and hence groundwater flow within the soil, so that there is a gradual drawdown of the **water table.** The concomitant desiccation of the landscape creates conditions which are unfavorable for the production of organic carbon, and hence fertility declines. Indeed, a comparison of the historical hydrological characteristics (indicated by soil characteristics) and the contemporary vegetation distribution suggested that there had been widespread desiccation of the landscape, and a **50% reduction in wetland areas**, probably over the last two decades.

Figure 4 (a) Example of erosion evident within wetland plots

Figure 4 b Example of headcut erosion

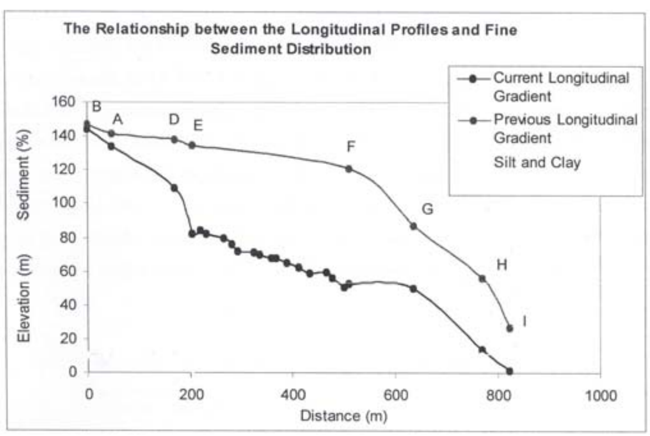


Figure 5 Previous and current longitudinal profile of Craigieburn wetlands (from Pollard *et al* 2005). Note that B-E and G-I are un-eroded sections whilst E-G is eroded. Section D-E is the headcut gulley

Hydrological simulations for a number of sub-catchments in the upper reaches indicate that wetlands contribute to hydrological functioning of the micro-catchment through the attenuation of peak discharges and increased baseflows. These results suggest that wetland degradation impacts through a reduction of base flows (Figure 6).

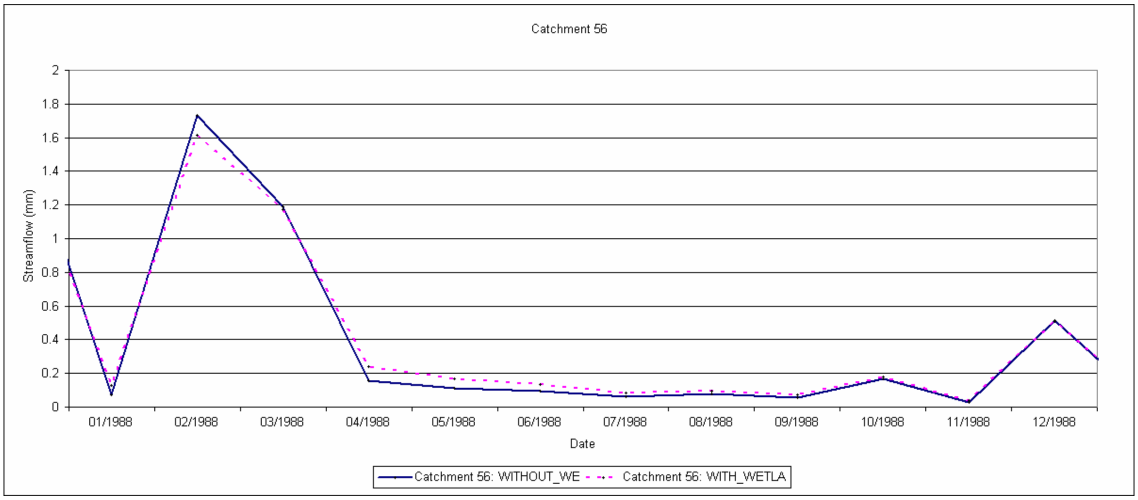


Figure 6 ACRU simulations of monthly stream flow with and without wetlands in the upper Sand River (ACRU catchment 62)

A key issues is the link between wetlands and the surrounding **micro-catchment**. On the hillsopes the lack of adequate vegetational cover, or soil and water conservation practices, as well as poorly-conserved fields all result in increase runoff and higher water velocities that, combined with the soil properties and an extensive path and track network that concentrates runoff, all contributes to the observed erosion (sheet deposits, rills and gullies). The consequence is decreased infiltration and an augmentation of peak discharges which in turn, exposes the wetland to greater risks from erosion. The impacts are (a) desiccation of the wetland (see above discussion on the loss of fine material, which acts as a 'plug' at the toe of the wetland); (b) increased levels of sediment loss from the hillslopes and deposition within the wetlands, further steepening the wetlands and increasing their vulnerability to erosion; and (c) increased levels of organic matter and nutrient losses from the system (see Pollard et al. 2005).

It is estimated that between 60 and 70%% of Craigieburn residents use wetlands to sustain their **livelihoods**. The overriding profile of wetland users is that of women between 35 and 70 years of age - mainly from single-headed households. In general, livelihoods are very vulnerable. A quarter of all households has minimal income and secures food through what they grow. Indeed, only 14% of users are regarded as well-off, whereas over half (60%) of users have limited income. Some 60% of households accessed their land by opening up fields without any permission or negotiation, pointing to the erosion of community-based governance. Equally striking is that 63% have accessed their fields in the last 10 years, citing hunger as the key driver. Craigieburn wetlands offer an important safety-net, particularly for the poor, and are estimated to contribute 40% of the food grown. However, within-wetland practices, the lack of governance and varying levels of awareness regarding wetlands are compromising the integrity of the wetlands and in turn, the livelihoods and catchment water security.

Within the wetlands, a number of landuse practices exacerbate erosion and hence desiccation, either directly but reducing soil structure or by increasing water velocity (see below and Figure 8). The associated reduction in fertility, also compounded by practices that directly reduced organic matter, result in reduced agricultural production. This has implications for peoples' livelihoods.

The study concluded that agricultural utilization of the wetlands should be based on the realization that wetlands derive their potential from high moisture and organic matter content of the soil. However wetlands tend to be highly sensitive and fragile. The following factors need consideration in rehabilitation and management and are important factors to consider in the **dynamic modeling**:

- The micro-catchment area has to allow rainwater to infiltrate, to slowly release this water subterraneously into the wetland and to have erosion from surface runoff reduced to the barest minimum.
- The wetland should have capacity to receive both catchment and incident water without being eroded, hold excess water and release it slowly into streams.
- The wetland must have capacity to accumulate organic matter.
- The wetland needs to be able to receive and accommodate soil and solute eroded from the micro-catchment area, and prevent the scouring and gullying, reducing siltation in the stream.
- The critical balance between inputs and outputs - water, nutrients and soil - has to be maintained.

Importantly, since the impacts on wetlands arise from interplay of within wetland activities **with** micro-catchment practices, both of these issues need to be addressed with full involvement of Craigieburn residents.

Use of the wetlands and farmer practices

As stated, Craigieburn wetlands are used mainly for subsistence agriculture. Farmers grow a variety of crops depending which zone of the wetland is used (see later) but by far the most commonly grown crop is

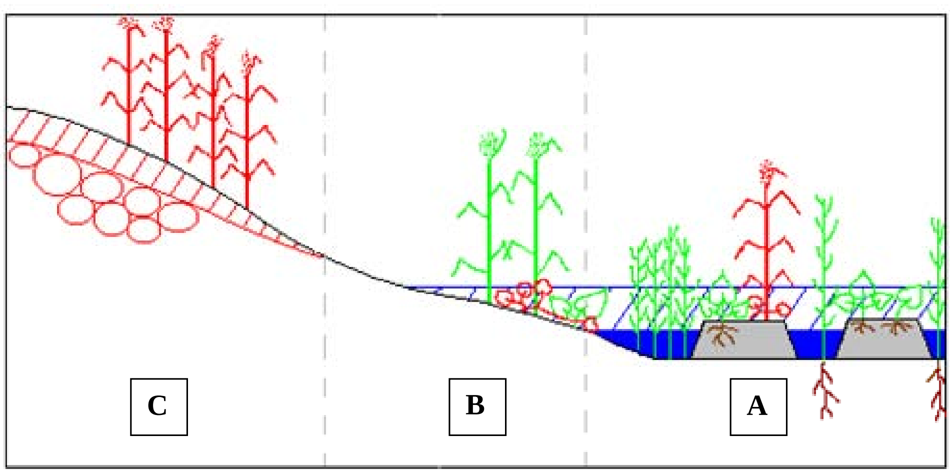


Figure 7 Three agro-eco zones that are used to characterise wetlands and cropping patterns in the Craigieburn wetlands.

Colocasia esculenta (marope). Together with farmers, three zones are recognised in the wetlands (Figure 7): Zones A, B and C (Zone A being the wettest and C, the driest).

The initial research in these wetlands (Pollard et al. 2005) revealed a range of farmer practices that had both negative and positive effects on wetland integrity. These are summarised in Table 2, which provides an analysis of how prevalent the practice is, and each practice is briefly reviewed below. Note that no fertilizers are applied in Craigieburn and hence this is not discussed.

Table 2
Summary of landuse practices and key characteristics of the wetland agro-ecosystem of Craigieburn based on baseline survey. This was based on visual assessments and on discussions with the farmers.

Feature	Detail
Eco-zones (see Figure 7) (n=42)	Many fields (38%) had all three zones. Just under a quarter (21%) had only B and C. Some fields have only zone C and they probably need a different approach
Bed orientation & furrow direction (n = 39)	Nearly 50 % of all fields have furrows that exclusively act to channel the runoff at higher speed (i.e parallel to incident runoff). A further 20% of fields also do so although they have a mix
Drainage (n= 38)	In almost all cases (90%) people are undertaking some form of drainage of the fields. Some 40% of this is extreme.
Fertility (n = 40)	Fertility is an issue in all but 7% of the fields. In 32% of cases it is very bad.
Weed quantity (n = 42)	Many fields have a moderate to bad weed problem. However, need to be cautious about what is considered to be a "weed" since for example, some herbaceous cover may be considered a weed in commercial agriculture but to local people these are edible greens.
Erosion (n= 39)	Nearly three-quarters of all fields (71%) have an erosion problem. Clearly this needs to be a focus of the work.
Cover (n = 42)	Only 20% of the fields visited had adequate cover. In 80% of the cases soil exposure was an issue.

Field/bed design

Firstly fields are cleared, and in many cases none of the indigenous vegetation remains. (This is problematic given that wetland plants are one of the features that give wetlands their unique characteristics).

Each farmer prepares their field into raised beds, separated by furrows. The **orientation** of these beds, together with their furrows acts to change the local hydraulic conditions and thus water velocity and erosion potential. This occurs in the case where beds and furrows lie parallel to flow (Appendix 1). Most (90%) of farmers undertake some form of drainage and in 40% of cases this was regarded as extreme. Half of these furrows act to channel the runoff at higher speed (i.e these are parallel to the incident runoff). A further 20% of fields also do so although they have a mix. In some cases, these effects are mitigated by **blocking** furrows – either manually or by planting reeds. Another aspect of bed 'design' is that of **staggering** the beds in the landscape such that water velocity is reduced, thereby reducing erosion. Some 71% of all fields assessed in 2005 showed signs of erosion.

Mulch/ cover

In terms of soil cover, fields in Craigieburn are poorly protected. Indeed, only 20% of the fields visited in 2005 had adequate cover as assessed by an agronomist. Over 80% of the cases, soil exposure was considered to be a major issue. Cover can be provided in one of 2 ways (a) through leafy plants, often achieved by intercropping and (b) through the use of mulch.

Manure application

There are two ways in which N is released: either through decomposition of organic matter or through the application of manure.

Farmers apply manure in about November after fields have been prepared. However, although highly prized, manure is in short supply and is not always available to all farmers in the quantities they desire. Generally it is stored, unprotected, on the side of the field until application when it is sprinkled on the soil surface and sometimes dug in. In Craigieburn the current impacts of manure application are thought to be low although farmers perceive the importance of manure to fertility as high.

Current efforts are attempting to encourage more conservative approaches to the application of manure. Manure serves to increase N.

Burning

Burning by farmers is undertaken to 'clear' an area in preparation for planting and also to reduce the risk of snakes and rats. Burning does not refer to a ground fire but rather the annual removal of vegetation, stacking it on a bed and then burning. This results in a substantial release of P, but also to the loss of N. In KwaZulu-Natal the annual burn in spring (September) had very little effect and did not reduce the soil organic matter (SOM). However, the impact in autumn (April- May) is greater in that the burning leaves the soil exposed for winter. However, for farmers burning releases P and could be regarded as a benefit (albeit shorterm).

Frequency of tillage

Tillage frequency is known to have a major impact on soil structure. Farmers start preparation of their field by clearing, burning and tillage in about September. Shallow tillage also takes place about three times a year. This involves forming mounds around the crop madumbes (*Coloscasia esculenta)*. Tillage impacts on soil temperature and increased oxygen resulting in oxidation (mineralisation) which impacts on SOM.

Resting of land

This refers to taking the field out of production for a year or more. Potentially cropped areas are left fallow and no cropping practices apply (manure application, mulching, burning, tillage/ hoeing). Resting is very uncommon in Craigieburn as farmers – under substantial pressure to produce food from limited resources- do not feel they have such an option. Indeed taking a field out of production occurs only by default when a farmer finds other work or with the death of the farmer or helper.

Crop production

The main crop grown in Craigieburn wetlands is *Coloscasia esculenta*, also known locally as madumbe (Tsonga) or marope (Sotho).

The variety of crops (Table 3) that is grown in wetlands is higher than that in drylands. This differentiation is also seen between zones in the wetlands (Figure 7). From observed crop types on each of the farmers' fields, some 14, 9 ad 5 crop types occurred in zones A, B, and C respectively. A number of points pertain to rehabilitation in this regard.

- Madumbes, maize and pumpkins are the most ubiquitous crops with madumbes being more common in the wetter zones and maize in the drier zones. Madumbes have a relatively high protein content.
- The variety of crops, and in particular the diversity of vegetables offer important sources of nutrition over longer periods of the year than would be available from dryland plots.

For the purposes of this work, and given their importance, madumbes will be used as the main crop under consideration.

The estimated yield is 2.5 kg/m^2 (or 25 tons/ha). In highly productive fields, the estimated yield is **30 tons/ha**, which is commensurate with estimates from elsewhere (e.g. (Kotze, et al. 2002). As mentioned above, fertility is a major issue for nearly all farmers. In a third of all fields visited, crops showed signs of major fertility problems. Field observations indicate signs of N deficiency (yellow-ish leaves, leaves narrower / a bit smaller than normal size are) and P deficiency (yellow-ish or purple-ish (color depends on species) stripes along leaves). Yet, none were observed on madumbes per se, but rather on maize leaves.

Table 3
Occurrence of crop varieties in plots of different wetland zones
(this information comes from an assessment at the end of the wet season and so may be under-representative of the full crop variety
***(source Pollard & du Toit, internal report*)**

CROP	A n =27	B n = 18	C n = 13
Maize	6	10	10
Sugarcane	7		
Root crop			
Madumbe	19	12	3
sweet potatoes		1	
Masetla		1	3
Vegetables			
Spinach	2		
Pumpkins	5	5	2
Tomatoes	1	3	
Cabbage	1	1	
Beans		2	1
Onions	2		
Nkaka	1		
Nuts	1		
Goundnuts	1		
bambara nuts	2	1	
Fruit			
Bananas	2		
watermelon	1		

In order to understand and represent multiple linkages between biophysical and anthropogenic factors, an overall system diagram was developed as part of Phase I (Figure 8). This model was used as the basis for the dynamic modeling to which was added the livelihoods component (see Part B).

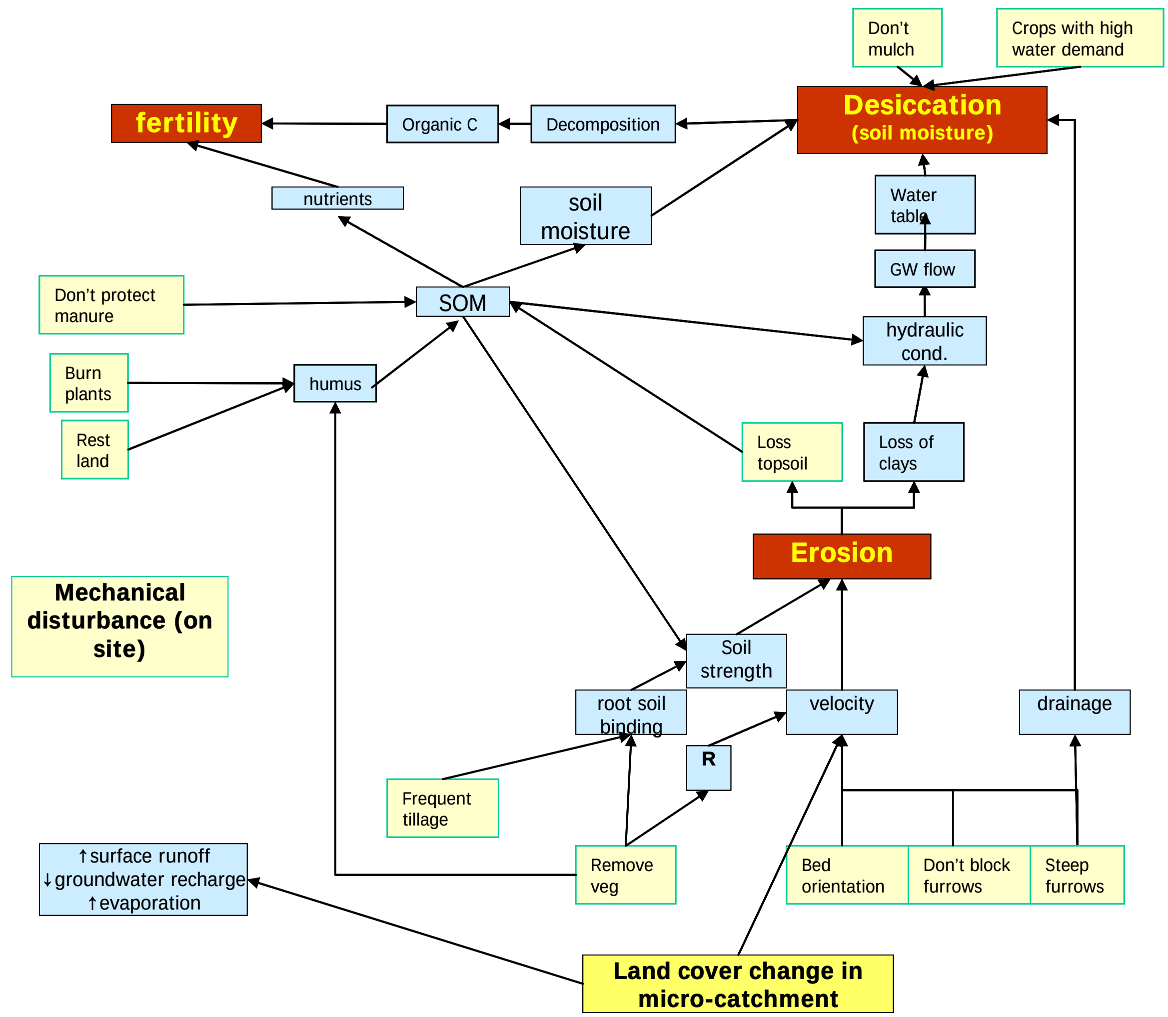


Figure 8 An overview of the linkages between on-site land use practices and wetland degradation, expressed through three key biophysical attributes (red boxes}. Headcut rehabilitation acts to control erosion and thus improve soil moisture and fertility (from Pollard et al. 2005). Velocity = water velocity; headcut (see Figure 4b)

Phase II, which flowed from this research was designed to support improved practices in order to rehabilitate the wetlands and therefore impact positively on peoples' livelihoods. This consists of three research components that accompany the farmers support programme. The first of these is the field assessments designed to track changing practices throughout the farmers support programme. Modeling as described in this report forms part of this component. Secondly, research is being undertaken to understand the learning processes associated with the development of wetland practices. This is being done through participatory methods and discourse analysis. Thirdly, indicators are being developed to assess the situation, to track change and to evaluate impacts.

The field assessments assess comprised a baseline survey (July- August 2005) and assessments at the start and end of each planting season. So far two assessments have been conducted. To do this, farmers plots were zoned into three agro-ecozones (A, B, C) according to where they lie within the wetland (Figure 7). Not all fields have all zones as shown in Figure 9.

Then the following information was collected from each plot:

- Water management [Contouring, bed orientation, presence of drainage furrows; blocking of furrows]
- Erosion [furrow slope, bare soil, bed height]
- Soil fertility [humus top soil; N fixers, live cover, mulch, burning, tillage]
- Wetland plants [extent, diversity]
- Crops [intercropping, water tolerant crops, weeds]

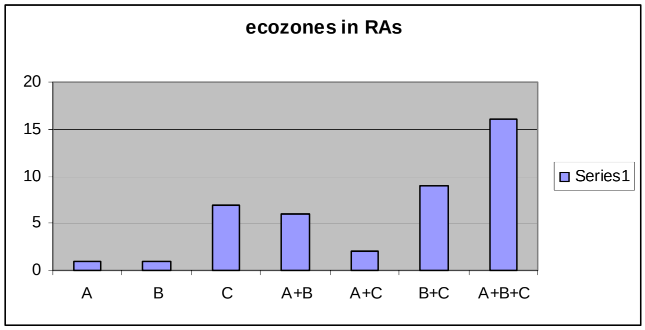


Figure 9 The composition wetland fields in terms of ecozones as assessed in 2005 (n=42)

The outputs from the baseline survey were then used as **information for the dynamic modeling**. Additionally information on factors and relationships were verified in the literature or, in cases where no information was available, data from the literature were sourced.

4. Key concepts and brief literature review

4.1 Key concepts and definitions

A number of terms and concepts that are used in the model are defined in Table 4 below and detailed in the following section.

A central concept for this work is that of **wetland health** since this provides the link between biophysical integrity, landuse practices and livelihoods. The tenet is that livelihoods in Craigieburn are partially supported by production from wetlands. Thus declining wetland health impacts on livelihoods through a decline in production.

However, what does *wetland health* mean? This merits some discussion. Despite the almost colloquial use of the term in the environmental field, few definitions of wetland health have been documented. The concept of wetland health - coined in response to the notion of wetland degradation - is used to describe some degree of deviation from a natural or functioning wetland. Some definitions are fairly stringent. For example, Macfarlane, et al. (2006) define wetland health as “a measure of the similarity of a wetland to the natural reference condition”. This definition reflects the objectives of their work which is to provide an approach to assessing change in wetlands. For other purposes however, although a system may deviate from natural, it may still be regarded as healthy in that production and resilience is maintained. For example, a small net loss of sediment or water at a certain time scale may not limit or significantly impact on production and may be replenished over a longer time scale. Thus scale is also an important dimension.

In the Craigieburn wetlands project, wetland health refers to the ability of the wetlands to sustain production through maintaining the water and sediment balance. Given this, plant production –of both crops and indigenous vegetation - is used as a proxy for wetland health (see Table 4).

Table 4
The following table provides a concise description of the variables and factors that comprise the dynamic model for Craigieburn wetlands. Where necessary, further discussion is also provided below.

Variable	Definition
Capillarity	This is the contribution of groundwater from the water table to the beds forms the **capillarity** contribution (in mm).
Crop water demand	Crop water demand refers to the amount of moisture a crop would use given an unlimited supply of water.
Denitrification	An (1) anaerobic biological reduction of nitrate nitrogen to nitrogen gas, (2) the removal of total nitrogen from a system, and/or (3) an anaerobic process that occurs when nitrite ions are reduced to nitrogen gas and bubbles are formed as a result of this process. Denitrification removes nitrate, an accessible nitrogen source for plants, from the soil and converts it to N_2 a much less tractable source of nitrogen that most plants cannot use. This decreases soil fertility making farming more expensive http://dwb.unl.edu/Teacher/NSF/C11/C11Links/www.bact.wisc.edu/
Erosion	Net loss of sediment from the system. In Craigieburn, erosion is considered at two scales: (a) sediment loss from hillsopes which contributes to wetland steepening and (b) sediment loss at a plot scale within the wetland which serves to deepen furrows thereby reducing the water table.
Efficient rainfall	A ratio that expresses the proportion of rainfall that infiltrates or that is 'lost' to runoff.
Field capacity	The maximum amount of water that a particular soil can hold. In wetlands, field capacity may be exceeded. More formally 'is the amount of soil water held in soil after excess water has drained away and the rate of downward movement has materially decreased, which usually takes place within 2–3 days after a rain or irrigation in pervious soils of uniform structure and texture".
Humus	In soil science, humus refers to organic, non-cellular, long-lasting component of soil. It is mostly extremely stable carbon compounds (hence organic) with no phosphorus or nitrogen that resists decomposition by microorganisms. Humus might, if conditions do not change, remain essentially as it is for centuries, or millennia. http://www.suprahumic.unina.it/) In agriculture, "humus" is often used simply to mean mature compost, or natural compost extracted from a forest or other spontaneous source for use to amend soil.
Hydric soil	Soil that formed under conditions of saturation, flooding, or ponding long enough during the growing season to develop anaerobic conditions in the upper part
Livelihoods	"The capabilities, assets and activities required for a means of living. A livelihood is sustainable when it can cope with and recover from stresses and shocks and maintain or enhance its capabilities and assets both now and in the future, while not undermining the natural resource base" (Chambers and Conway 1992). In general, livelihood assets, comprising natural, physical, social, human and financial capital, provide people with the basis to construct a *livelihood strategy*. Particularly in the case of the poor and vulnerable, a *multiple* livelihood strategy reduces vulnerability to shocks and stresses.
Mineralisation	In biology, mineralisation is the process where a substance is converted from an organic substance to an inorganic substance, thereby becoming mineralised. In soil science, mineralisation is used to describe the release of organic compounds during decomposition into plant-accessible forms
Mulching	Mulch is a protective cover placed over the soil, primarily to modify the effects of the local climate. A wide variety of natural and synthetic materials are used (see also Section 4.2)
Organic matter	Organic matter is matter which has come from a recently living organism; is capable of decay, or the product of decay; or is composed of organic compounds. The definition of organic matter varies upon the subject it is being used for. In soil science the term soil organic matter may include both decaying materials and humic substances (humus).
Resting/ fallow	Removing a field from production for a year or more (leave field fallow)
Sustainabaility (agricultural) www.soils.org	Managing soil and crop cultural practices so as not to degrade or impair environmental quality on or off site, and without eventually reducing yield potential as a result of the chosen practice through exhaustion of either on-site resources or non-renewable inputs.
Tillage and tillage frequency	The mechanical manipulation of the soil profile for any purpose; but in agriculture it is usually restricted to modifying soil conditions and/or managing crop residues and/or weeds and/or incorporating chemicals for crop production.www.soils.org In this case, refers to deep hoeing involved in the preparation and harvesting of corms. In

	Craigieburn, shallow tillage also takes place to form mounds around the madumbes.
Transpiration: ETa and Etm **ETm (climatic demand for water)**	ETa / Etm ratio is good indicator of plant stress ETm typically represents the climatic demand for water ETp X Kc where Kc = crop factor, represents the physiological status of the crop. Ideally, for maximum production, water should be available throughout the cropping season and meet the plant's needs at each steps of its growing cycle, i.e. water content should be close to field capacity most of the time. In such conditions (and with no other major limiting factor – radiation, lack of nutrients, diseases or pests), crops will extract soil water at ETm and photosynthesize optimally. In real conditions, soils get dry and crops evaporate only a fraction of ETm since water is less available and more difficult to extract. Such fraction of ETm is actual evapotranspiration (Eta). When the soil water content reaches permanent wilting point PWP, ETa becomes nil and the crop wilts and dies. Therefore, the ratio ETa / ETm (monitored according to water balance methodologies) is a good indicator of crop water stress, and of production.
Eta **Actual evapotranspiration**	Actual evapotranspiration. ETa is the actual crop water consumption. When the soil water content reaches permanent wilting point PWP, ETa becomes nil and the crop wilts and dies. It is a fraction of the Etm.
Etp **Potential evapotranspiration**	ETp, or potential evapotranspiration as a factor of wind, air temperature and quantity of solar radiation. Sometimes called **Potential evapotranspiration** (**PET**) is a representation of the environmental demand for evapotranspiration and represents the evapotranspiration rate of a short green crop, completely shading the ground, of uniform height and with adequate water status in the soil profile. It is a reflection of the energy available to evaporate water, and of the wind available to transport the water vapour from the ground up into the lower atmosphere. Evapotranspiration is said to equal potential evapotranspiration when there is ample water.
Wetland health	In the Craigieburn wetlands project, wetland health refers to the ability of the wetlands to sustain production through maintaining the water and sediment balance. A component of this includes continued water security at a micro-catchment level. Knowing that farmer practices are impacting on the wetlands, the objective of the work reported herein is to qualify these impacts and to understand if an improvement in practices would lead to an overall improvement in wetland health. Within this context, we wish to understand if improved practices lead to improved crop production and hence improved livelihood security. Given this focus, we have chosen to select one aspect of wetland health – that of plant/crop production – to represent wetland health. The assumption is that if plant production is maintained then the wetland can be regarded as healthy in that it continues to deliver this key provisioning service and that the underlying supporting services have been maintained.
Wilting point	**Permanent wilting point** (**PWP**) or **wilting point** (**WP**) is defined as the minimum soil moisture at which a plant wilts and can no longer recover its turgidity when placed in a saturated atmosphere for 12 hours. the PWP values under field conditions are not constant for any given soil, but are determined by the integrated effects of plant, soil and atmospheric conditions

4.2 A brief literature review of landuse practices and wetland crop production

A stated, a major threat for the Craigieburn wetlands is that of erosion which refers to both headcut erosion within the stream channel and erosion from hillslopes and wetland surfaces. Ultimately, hillslope and wetland sediment inputs onto the channel lead to increased steepness and vulnerability to headcut erosion (see Figure 4) which leads to desiccation, and a reduction in fertility (and hence production) as well as a loss of wetland extent.

Although the staple food in Craigieburn is maize meal, it has been explained that the madumbes are the major crops grown in wetlands, and to a lesser extent, pumpkins and other crops as indicated in Table 3. Importantly therefore wetland crops introduce variety into the diets of local residents. Madumbes are eaten in great abundance between April to June, but not much after that because they are susceptible to post-harvest decay, and do not to store well. Pumpkins, which store well, are available from April well into winter, depending on the amount that is produced.

The nutritional value of a food depends upon its nutritional contents and their digestibility and the presence or absence of anti-nutrients and toxic factors. Madumbes or *Colocasia esculenta*, commonly known as taro or cocoyam, is an important food staple of developing countries in Africa, the West Indies, the Pacific region and Asia (Cabie and Furguson, 2003). The corms are generally used as the main starch in meals. For supplying nutrients, the corms may be considered as a good source of carbohydrates and potassium (see source: http://www.siu.edu/~ebl/leaflets/taro.htm). Large servings of taro corms become a significant source of dietary protein, especially if taken more than once a day. Taro also contains greater amounts of vitamin B-complex than whole milk. The cooked leaves have the same nutritional value of spinach.

Although no studies have been undertaken specifically on soil fertility in Craigieburn, it shares similar soils (sandy, derived from underlying granite) with extensive areas of Zimbabwe, for which extensive research has been conducted. This includes much research dealing with issues faced specifically by smallholder farmers (e.g. Giller et al., 1998; Grant, 1967; 1970; 1993; Mapfumo et al., 1998; Mtambanengwe, 1998; Mugwira and Murwira, 1998; Murwira and Nzuma, 1999; Nzuma et al., 1998, van Straaten, 1999), which further adds to its relevance to Craigieburn. Craigieburn is also located on granites and has similar climatic and edaphic features to Zimbabwe. A large proportion of Zimbabwe is covered with sandy soil derived from coarse granite. Both also share a maize-based farming systems. Thus, the considerable literature existing on the soil fertility of Zimbabwe has great relevance to Craigieburn.

The sandy, granitic sands of Zimbabwe are typically low in N, P and S as well as having low CEC due to low clay and organic matter contents, and are generally acidic (Mugwira and Murwira, 1998). "Many croplands on granitic sandy soils in the communal areas that have been cropped without regular applications of manure or inorganic fertilizers now show multiple nutrient deficiencies of N, P and S and sometimes Mg and K, as well as micronutrients such as zinc" (Grant, 1970, cited in Mugwira and Murwira, 1998). The wetlands granitic, sandy landscapes typically have higher soil organic matter levels than non-wetlands (e.g. wetland: 2.1% total carbon, wetland margin: 1.5%, and adjacent non-wetland: 0.5% (Grant, 1998). Thus, given that the N stocks in particular in a soil are strongly linked to the SOM level (Buresh and Giller, 1998) one would expect the nutrient stocks in wetlands to be generally higher than non-wetlands. However, although the cropping potential of wetlands in these landscapes are high, these wetlands are also typically low in N, P and S, as for the corresponding non-wetland areas. Many of these wetlands are also acidic (Grant, 1993), and thus they are also susceptible to nutrient deficiencies where there has been inadequate application of nutrients. Grant (1993) recommends "To get the benefit of the dambo (wetland) moisture, fertilizers or manure must be applied."

The nutrient cycling in the Craigieburn wetland is represented in Figures 10 and 11. These are based on figures for nutrient cycling in cultivated wetlands generally, but tailored for the particular circumstances encountered at Craigieburn. Those nutrient inputs/losses and stocks represented in Figures 3 and 4 which are considered to be negligible (e.g. levels of dissolved P influent waters) have been omitted.

In P there are 8 different flows that need to be considered, and 3 of these are closely linked to erosion/deposition, which is already being described elsewhere in the overall dynamic modeling being undertaken for Craigieburn. In N there are 13 flows that need to be considered, with several of these such as denitrification very difficult to make generalized estimates.

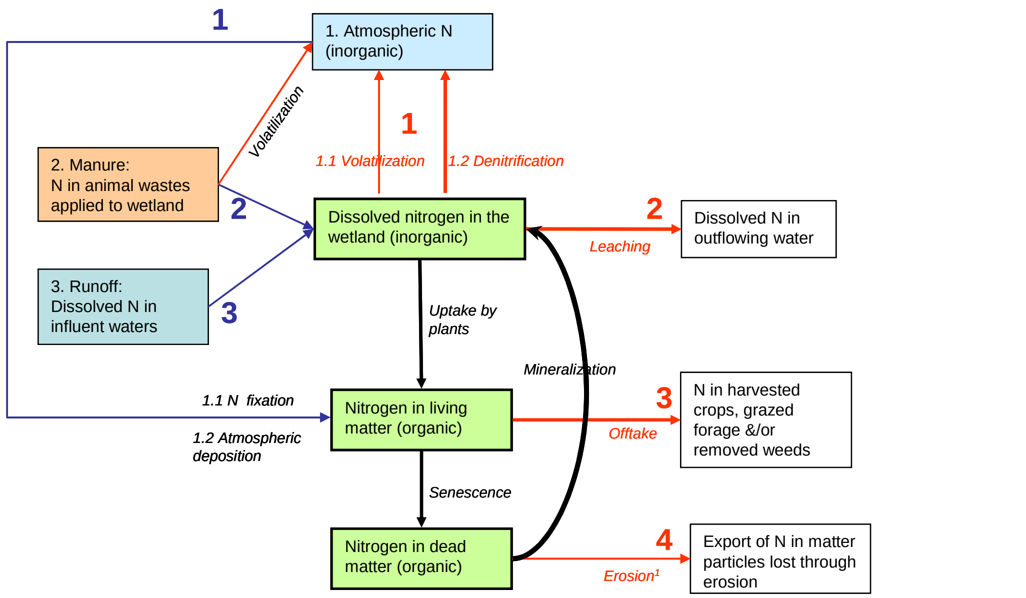


Figure 10 The cycling of nitrogen in a wetland based on the wetland and landuse practices (numbers refer to various input and output paths). The relative magnitude of nutrient flows is represented by arrow thickness [1] Relative to leaching, this loss is generally low, unless erosion is severe.

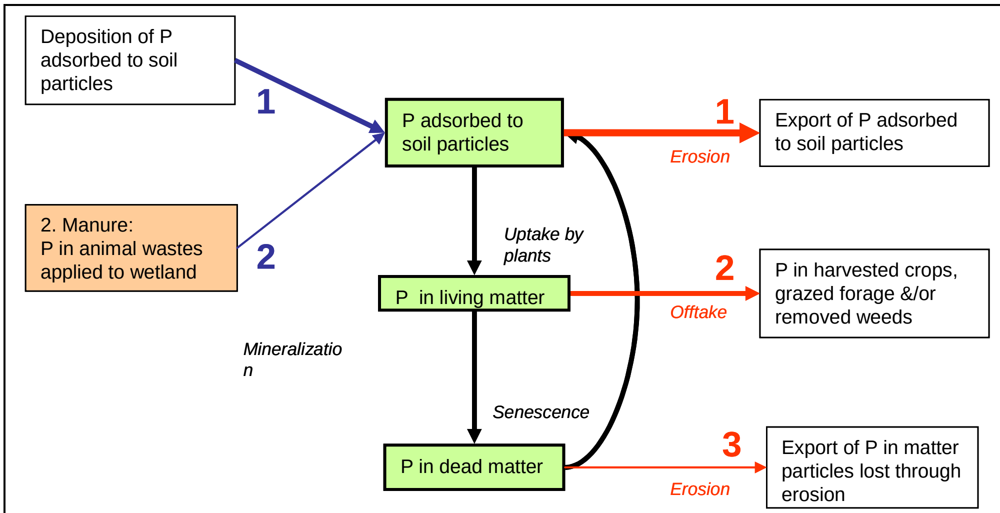


Figure 11 The cycling of phosphorus in a wetland based on the wetland and landuse practices. The relative magnitude of nutrient flows is represented

In terms of agricultural practices, mulch or cover has been shown to have by far the greatest impact on taro yields in Hawaii. Mulching is well-recognised as an extremely important practice that is used for the following benefits:

- to moderate soil temperature;
- to retain water by slowing evaporation;
- for erosion control since it protects soil from rain and preserves moisture
- for sediment control – slows runoff velocity;
- to control weeds by blocking the sunlight necessary for germination;
- to add organic matter and nutrients to the soil (decomposition);
- to repel insects;
- to incrementally improve growing conditions by reflecting sunlight upwards to the plants, and by providing a clean, dry surface for ground-lying fruit such as squash and melons.

The major difference in taro yield was between mulched and non-mulched (bare-soil) plots. Weed control was adequate in all treatments, but fresh corm yield and the percentage of corm dry matter were significantly greater due to mulch effects (Miyasaka et al. 2001*).* Soil organic carbon, total N, and exchangeable calcium and magnesium were greater in mulched plots. However the authors caution that there were high costs of organic inputs and profit was not much higher although in the longer term would improve soil structure and reduce erosion thereby ultimately improving yield. Some mention is also made of weeding but the results are ambivalent seemingly due to the interactions between 'weeds', soil cover and stability and the decline in nutrients.

To our knowledge no literature is available that examines the impacts of bed orientation or furrow direction within wetlands and their effects on production.

PART B
DYNAMIC MODELING IN WETLAND ENVIRONMENTS: MODEL DESIGN AND INPUTS

5.1 Overall approach

Conceptually our starting point was to develop an overarching systems diagram that linked the micro-catchment, its wetland and the livelihoods of its residents. This model, summarised in Figure 12, indicates the linkages between landuse practices and wetland health, which in this study this refers to the wetland production capacity, see Table 4). Wetland health is predicated in water and sediment balance which may change as a consequence of changes on the hillslope and/or within the wetlands. Plant and crop production contribute to food and household products which are mainly used for household consumption. These represent the natural and financial capital inputs to peoples' livelihoods. From this conceptualization it is clear that ecosystem health is directly linked to peoples' well-being. The wetlands-livelihoods component was further refined to guide the modeling exercise.

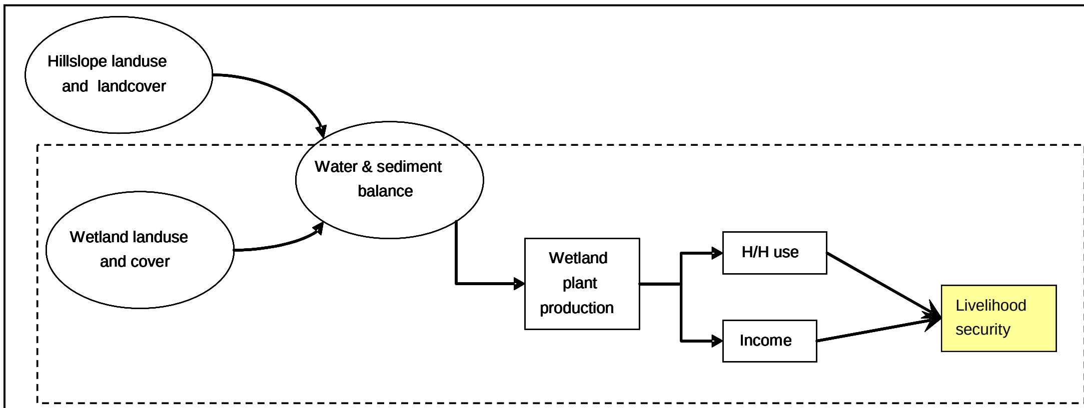


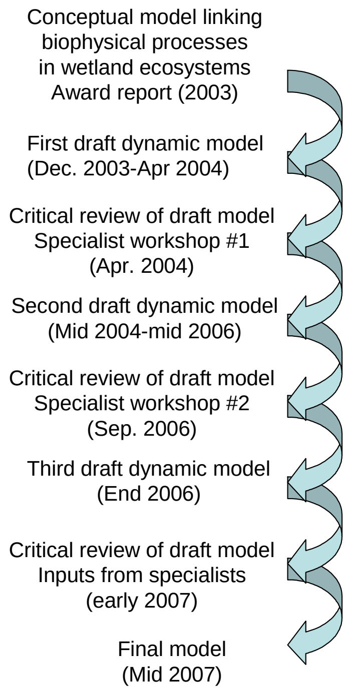
Figure 12 Overall conceptual model linking micro-catchment and wetland practices, wetland health (production) and livelihoods. The boxed component is the focus of the modeling exercise and is elaborated in Figure 13. H/H = household

The wetlands offer a range of goods and services (Pollard et al. 2007) but by far the most important is crop production. Thus we decided to limit the scope of the model to interactions between agricultural practices, environmental impacts and livelihoods. This is because any model has to be bound, so that it remains doable, realistic. The ridged bed for madumbe cropping is here the central object for modeling, with its close environment. Thereafter we considered the full range of farmer practices (see Table 3) and, based on current understanding of these (see Section 4) and our interactions with wetland users over the past three years, a series of questions was derived that we hoped to explore through dynamic modeling. This involved a multidisciplinary approach linking the disciplines of geomorphology, hydrology, ecology, agronomy, sociology and environmental education.

The challenge for this team in the initial stages was to examine and validate the preliminary model, not only to provide details on relationships between variables in their field of expertise but also to think beyond their 'comfort zone' into a scale captured in the above diagram. This meant also understanding the 'web' of sub-systems that comprise such a system. Thus a key focus of the work was to move some way towards

integrating biophysical, social and economic aspects of Craigieburn's wetland use into a meaningful – if incomplete – picture. This would also serve to highlight essential research required to build a more complete snapshot of reality.

The overall process that was followed for the team which consisted of the aforementioned disciplines was as follows:



It was clear from these discussions and previous work (Pollard & du Toit 2006, internal report) that scale and zonation were important issues. The impacts of a certain landuse practice in the wettest areas may differ considerably from the same practice in a drier area, for example. Given this we hoped to consider the micro-catchment as comprising four zones: the uplands and the three zones of the wetlands: A, B and C (see Figure 7). However as the work proceeded it became clear that despite the substantial work in Craigieburn wetland, there still exists a dearth of data of the type needed for meaningful input to dynamic modeling. Although linkages had been established by early research, (as discussed later), far less was known about the relationships between these variables. A major challenge was to populate the model with meaningful data especially where data were lacking. In many cases therefore, these relationship were derived from the literature or through expert opinion at the specialist workshop.

Another major constraint was that of the model itself. The lack of spatialisation within dynamic modeling makes it difficult to develop and test certain scenarios in any realistic and plausible way. The relationships between factors – or groups of factors – are influenced by their position in the landscape, so that for example, the impacts of sediment generation in Zone C may influence fertility development in Zone A. This problem associated with dynamic modeling is widely recognised and has led to the development of spatialised agent-based models. Such an undertaking was, however, beyond the bounds of the work reported herein. Finally therefore we limited our modeling to Zone A – the wettest part of the wetland - and explored patterns rather than detail.

5.2 Key questions and scenario generation

A number of key questions guided the model design. Many of these questions emanated from discussions with the farmers and through discussions at the specialist workshops. Final scenarios were also refined through from sensitivity analysis, which helped tp identify which combination of control variables[2] (mostly cropping practices) lead to better or worse outcomes in terms of conservation or degradation, respectively As mentioned earlier, these focused on exploring the impacts of different landuse practices on wetland health and livelihoods. For practical purposes, these changes in practices were then grouped and used to generate scenarios.

The key questions were as follows.

Overall field management on wetland health

1. What impact is resting likely to have on wetland health?

Bed design

2. What is the impact that each of the following is likely to have on wetland health:
   - Re-orientation of beds
   - Blocking of furrows
   - Staggering of beds to reduce water velocity.

Bed preparation

1. What impact is the use of minimum **tillage techniques**- currently being supported through the farmer support programme - likely to have on wetland health?
2. What impact is **mulching** and/or live cover – thought to be considerable - likely to have on wetland health?
3. What impact is increased **manure** application, employing conservation tillage techniques, likely to have on wetland health?
4. What impact is not **burning** likely to have on wetland health? (It is assumed that if farmers stop burning cleared vegetation, this will be available for mulching).

Overall micro-catchment management

1. What impact does a major rainfall event have?

In view of the aforementioned questions, a number of scenarios were explored through dynamic modeling (Table 5). In order to define a baseline scenario under madumbe production, the common current practices were used based on the 2005 assessment (see Table 2). Further details are provided in Section 5.3.1. It was also recognised that certain practices are relatively easy for a farmer to implement whilst others would be much more difficult. Based on field experience, those that constitute 'relatively easy' changes would include mulching, blocking of furrows in the dry season and leaving portions of indigenous vegetation in the wetland. Other practices are much more labour intensive, and so prior to suggesting changes, we wanted some idea of how important their impacts would be. These included staggering of beds, the re-orientation of beds and implementing soil and water conservation throughout the micro-catchment.

[2] Any variable may be a control (or forcing or input or independent) variable, depending upon context. Such variable will form the main input to a sub-model. It may also be an output variable (outcome) of another sub-model.

Table 5
Summary of the scenarios explored through dynamic modeling. Note that for all scenarios, production area is 0.0182 ha per household. Household composition = 2 adults, 4 children. The impacts of rainfall events are included in Scenarios 3.3(b) and 3.4(c)

Scenario	Description
0. Scenario 0	**Baseline: Current situation**. Poor land use practices + high erosion risk • All fields with furrows (drainage). • 50% of furrows parallel to flow direction • Moderate erosion on 75% of fields (5.63 t/ha/a: runoff carrying capacity depends on runoff intensity and soil structure (20g/l - 50g/l if soil is very damaged + runoff is strong). • Over 80% of fields with inadequate/ no cover • Beds left fallow from April 1 onwards • Tillage / bed preparation on September 22 • Planting on October 1, harvesting on March 31 (181 day-cycle) • Crop residues and weeds may be used for mulching (if mulching is chosen) or burnt (if burning is chosen) or just set aside • Rainfall (1995) = 1021 mm (slightly below average) • No sale of madumbe, production is self-consumed, apart from that set aside for planting. Optimal yield not reached due to water and N stress (30 t/ha/a or 546 kg per household plot of 0.0182 ha). In reality, it was assumed that household yield is about 450 kg (25 t/ha/a), and 25% of this is set aside (113 kg).
1. Bed management	
Scenario 1.1:	Scenario 0 + beds oriented perpendicular to main stream flow
Scenario 1.2 (a)	Scenario 0 + furrows blocked Furrow blockages used as a water retention strategy during low flows and the farmers remove the blockages during high flow periods.
Scenario 1.2 (b)	Scenario 0 + furrows are blocked and + beds staggered (water flows much slower in between beds and level of water increases). Furrow blockages used as a water retention strategy during low flows and the farmers remove the blockages during high flow periods.
Scenario 1.3 (a)	Scenario 1.2 + manuring (5 kg fresh manure/m^2) This examines the effect of serious manure application, which is higher than most farmers are able to apply.
Scenario 1.3 (b)	Scenario 1.2 + manuring (2 kg fresh manure/m^2)
2. Effects of mulching, resting and manuring	
Scenario 2.1 (a)	Scenario 0 + mulching
Scenario 2.1 (b)	Scenario 0 + mulching + December rainfall event
Scenario 2.2 (a)	Scenario 0 + 0.5 kg dose of fresh manure/m^2
Scenario 2.2 (b)	Scenario 0 + 0.5 kg dose of fresh manure/m^2 + mulching
Scenario 2.3	Scenario 0 + resting of land in year 3 (no cropping in 2nd full cropping season)
3. Effects of aggressive practices (weeding and burning)	
Scenario 3.1	Scenario 0 + burning all surface vegetation before tillage/preparation Sep.15
Scenario 3.2	Scenario 0 + weeding in December
Scenario 3.3 (a)	Scenario 0 + weeding in January (synchronizes with heavy rainfall)
Scenario 3.3 (b)	Scenario 0 + weeding in January + rainfall event
Scenario 3.4 (a)	Scenario 0 + weeding in November, December, January, February
Scenario 3.4 (b)	Scenario 0 + weeding in November, December, January, February + burning
Scenario 3.4 (c)	Scenario 3.4 b + rainfall event in November.
4. Permanent Resting	
Scenario 4.1	Four years with no cropping / back to fallow land

5.3 Model design and inputs to modeling the wetland agro-ecosystems (Zone A)

This section presents the dynamic model that **represents the functioning of ridged beds under various cropping practices, and the interactions with local hydrological factors** (i.e. in the riverine wetland agro-ecosystem or Zone A). The overall model, used as the basis for the Stella dynamic modeling, is summarised in Figure 13. It is presented below as separate sub-models (six sectors) that are interconnected via several common state and control variables. For instance, one given state variable in a sub-model may become a control variable into another model. Such is the case for humus content, soil structure and the like. Also, several control variables are used in several sub-models. As noted, data on the relationships between these variables varied considerably and is discussed below.

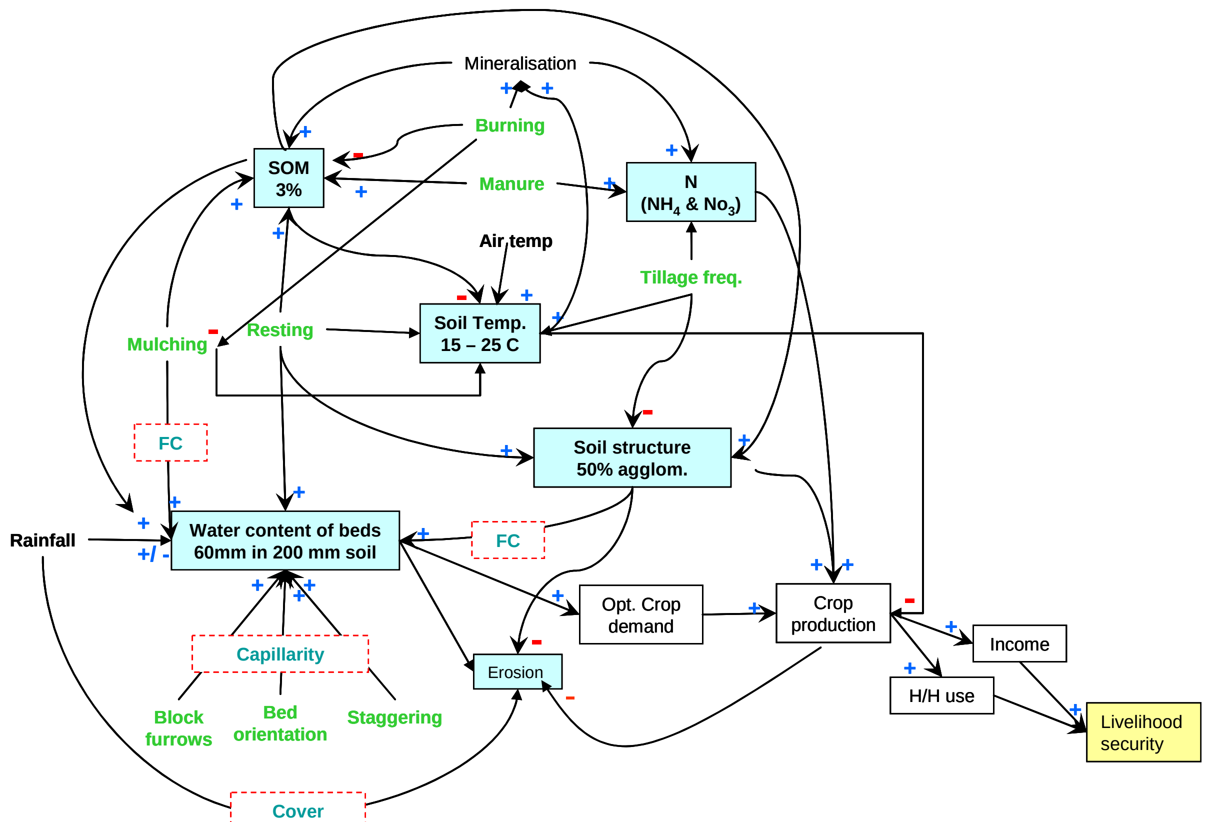


Figure 13 System diagrams representing the linkages between landuse practices in Craigieburn wetlands (green text), biophysical aspects, and wetland production as a contribution to peoples' livelihoods. This was used to guide the development of the Stella model. The sub-models are indicated as blue boxes

5.3.1 Generalities and main control variables

The model assumes that headcut erosion (which moves upstream within the streambed) is stable (see Section 3.2).

A **household** composition is two adults and four children. For all scenarios, production area is 0.0182 ha per household since, on average, each household has a total area of 182 m^2 for madumbe production. The model time step unit is the **day**. The model is set to run for 1460 steps i.e. 4 years[3]. The calendar starts on January 1st (year 1) and ends on December 31st (year 4).

The model operates on a **per-hectare** basis when area is concerned, and it considers the first **0.2 meters** of soil layer that are tilled and form most of the support medium to the crops[4]. Soil bulk density is considered 1300 kg m^{-3}. **Field capacity** (which determines the maximum water content) is set at 60mm (30% volumetric water content; Prof. Ellery, UKZN, pers. comm.). It may evolve according to humus content (decrease or increase below or above 2% humus content). It is also impacted upon by soil structure (decrease or increase below or above 50% soil structure).

Actual **rainfall data** from year 1995 are used, as daily precipitations collected in Craigieburn (Wales station, num. 594819, alt. 730m, long. $30^0$58', lat. $24^0$39'). Year 1995 represents an average climatic year. For the sake of clarity and excluding additional disturbance into the model's outcomes, this particular year is repeated 4 times, over the 4 years. Also, the model allows for including special, extra events (heavy rainfall) at times. These may be summer rainfalls (50mm per day for 3 days in October, November, December, January, February or March) and winter rainfalls (20mm per day for 2 days in June, July, August or September). For each of these scenarios, days 20-21-22 or days 20-21 have been selected within summer and winter months respectively. For instance, if extra rainfall is tested in March, there will be additional 50mm each day on March 20, 21 and 22.

The relationship between ambient **temperatures** and soil temperature is not well understood but is dealt with in the beds fertility sub-model (tillage, resting and water content). The main assumed impact is on mineralisation and the release of N.

An overarching control variable is "resting of land", as a dummy (0/1 for off/on) that can apply any chosen year, for the whole of that year. If set to 1 (on), then potentially cropped areas are left fallow, no cropping practice applies, nor has an impact onto the systems.

The **crop** under consideration is the most ubiquitous wetland crop, madumbes (*Colocasia esculenta*), which are grown over 181 days, between Oct 1st and March 31st (For the model, harvest occurs systematically on march 31st but in reality harvesting can occur through to May). From discussions with farmers during harvest time (early May 2007), the estimated optimal yield is 3 kg/m^2/a, so that with an average area for madumbe cropping of 182 m^2 for madumbes. The maximum yield per farmer is thus 546 kg of madumbes per household. However, in reality yields actually prove lower since stresses and low density affect production. On account of these limiting conditions, we assumed that the average farmer would target a yield of about 450kg, of which 25% (113kg) are retained for planting as seed corms (i.e. 2.5 kg/m^2/a). Such

[3] Since the model runs on a daily basis (mostly because of water balance requirements), we have met Stella's limitations in terms of total time which is 1500 steps, hence 1500 days, hence about 4 years

[4] Note that all scenarios start with similar conditions i.e.: - Water content = nominal field capacity (60mm); - NH_4 = 700 kg/ha; - NO_3 = 100 kg/ha; - SOM = 0.03 kg/ kg (3% mass); - Soil structure index = 50%.

amount is systematically set aside from sales or self consumption, whatever real yield is. The current price for madumbes is R3.5 per kg.

Possible **cropping / farming practice**s include (1) burning (before planting, set on September 15), tillage / bed preparation (before planting, set on September 22), (2) manure application (at planting, set on October 1), (3) weeding of beds (may be on Nov.15 and/or Dec.15 and/or Jan.15 and/or Feb.15). All may be set to 1 (on) or (off). Other practices include (4) mulching (dead vegetation left to cover), (5) orientation of beds (parallel or perpendicular to stream flow), (6) staggering of beds (beds aligned or staggered), and (7) blocking water flow in furrows (farmers stuff furrows with vegetation or soil). If set to 1, each would apply throughout the model running, unless "resting of land'" is on.

All these "practices" have been identified as having a high impact upon the functioning of madumbes' bio-physical environment. Such an environment has been clustered into interconnected sectors for modeling. Certain sectors directly impact upon madumbe production (e.g. N dynamics, water balance) whilst others refer to the long term fertility and sustainability of the system (e.g. structure, organic matter, erosion)[5]. These sectors are presented below, with no specific order. Since they are all interconnected and interdependent it is essential to cross information between sectors for understanding.

Model validation has been performed through comparing the model's outcomes (output variables, see Table 6) with figures mentioned in the literature, or with expert views, or with field measurements when possible (e.g. volumetric water content with TDR device). All figures shown by output variables seem compatible with those, be there on livelihoods (income from madumbe sales), or biophysical aspects (annual soil loss, days under N or water stress during cropping cycle, etc.). Sensitivity analysis (i.e. running the model under varying input variables and the identification of the most effective outcomes) has been performed with the dual purpose of (a) testing the robustness of- and validating the model, and (b) of identifying the most important control/input variables. This was a complex and lengthy process owing to the large number of input and output variables, and to composite output variables (e.g. number of days under water stress), leading to a vast number of simulation and resulting outcomes. These are summarised per scenario.

Table 6
Summary of the input and output variables and modules used.

Forcing/input variables	Modeling modules	Model outputs
Rainfall (time series; 0-69.3mm) Extra rainfall events (0, 20 or 50mm) Evapotranspiration max (time series; 2.7-5.5mm) Air temperature (time series; 24-29 dc) Weeding (dummy) Tillage (dummy) Burning (dummy) Fallowing (dummy) Mulching (dummy) Bed orientation (dummy) Bed staggering (dummy) Blocking of furrow (dummy) Manuring (0-50000 kg)	Water balance Soil erosion Soil structure Soil organic matter Nitrogen balance Soil temperature Yearly production Income and food	Water stress (number of days during crop cycle) Soil loss (mass per ha per year) Nitrogen stress (number of days during crop cycle) Actual production (kg per household per crop cycle) Yearly income per household (Rand) Daily energy intake per capita (kJ)

[5] *Readers may access the Soil Science Society of America website for more detailed definitions of the words used here: https://www.soils.org/sssagloss/index.php*

5.3.2 Dynamics of soil organic matter

A first sub model addresses the dynamics of soil organic matter, or SOM (see Figure 14). Table 7 shows the control variables impacting upon SOM content, while Box 1 displays more details in relations between variables.

The model oversimplifies the dynamics of SOM and does not consider the actual complex processes at stake (humification, mineralization / re-organization balance, N dynamics, diversity of forms of SOM, microfauna activity, etc.). Inspired by field observations and literature (as reviewed in previous sections; Morel, 1989; Bonneau & Souchier, 1979), it tries to mimic the trends in accumulation or decrease owing to discrete practices (e.g. burning, tillage, weeding, manuring) or continuous processes, as indicated below. Mineralization means here an overall molecular simplification of elements constituting SOM, away from humus and complex components (e.g. amino-acids, glucids).

The key state variable is **total organic matter content** or SOM (mass kg SOM/ kg soil). Detailed equations and relationships are provided in Box 1.

The initial SOM value is 0.03%. The model considers that below that level, most of SOM content is humus or complex organic matter (80 to 90%) which will hardly mineralize under normal conditions over a span of few years. Further, only a portion of non-humic SOM may mineralize on a yearly basis (about 50%). This is why SOM mineralization is a function of SOM content amongst other factors. Mineralization depends also on soil temperature (0 below 10^{o}C, maximum above 20^{o}C) and on water content (maximum between 15% and 30%, otherwise lower). Both factors impact upon microfauna activity. When spread over madumbes beds, manure immediately releases 5% content in the form of mineral elements which will not pool into SOM (see N model).

Burning and tillage will trigger significant mineralization and SOM destruction, resulting in losses, while resting of land, manure application and mulching increase SOM content via accumulation.

Table 7
Description of control variables and processes impacting upon total SOM

Control variables	Effect	Description of effect	Specifications	Range / unit
Resting of land	0 / +	Increase by 1.10^{-5} kg SOM per kg soil daily through decomposition of natural vegetation	Permanent over a chosen year Dummy (off/on)	0 or 1 (switch)
Mulching	0 / +	Increase by 1.10^{-5} kg SOM per kg soil daily through decomposition of vegetation	Permanent Dummy (off/on)	0 or 1 (switch)
Manure application	0 / +	Dry mass accumulation, 0 to 0.02 kg SOM per kg soil	Pulse: once a year, October 1 (day #274) Dry matter content: 0.6 5% immediately released (N)	0 to 28500 kg/ha (dry matter) (knob input device)
Burning	0 / -	Decrease by 1% the SOM content on the day it occurs	Pulse: once a year, September 15 (day #258) Dummy (off/on)	0 or 1 (switch)
Tillage	0 / -	Decrease by 2% the SOM content on the day it occurs	Pulse: once a year, September 22 (day #265) Dummy (off/on)	0 or 1 (switch)
Weeding	0 / -	Decrease by 1% the SOM content on the day it occurs	Pulse: up to 4 times a year, Nov.15, Dec.15, Jan 15 and/or Feb.15 (days #319, 349, 15, 46) Dummy (off/on)	0 or 1 (switch)
Mineralization	-	Loss in SOM through breakdown of long, complex organic molecules	Permanent Depends on temperature, water content, SOM content and cropping practices (see above)	0 to 0.0006 kg SOM / kg soil daily

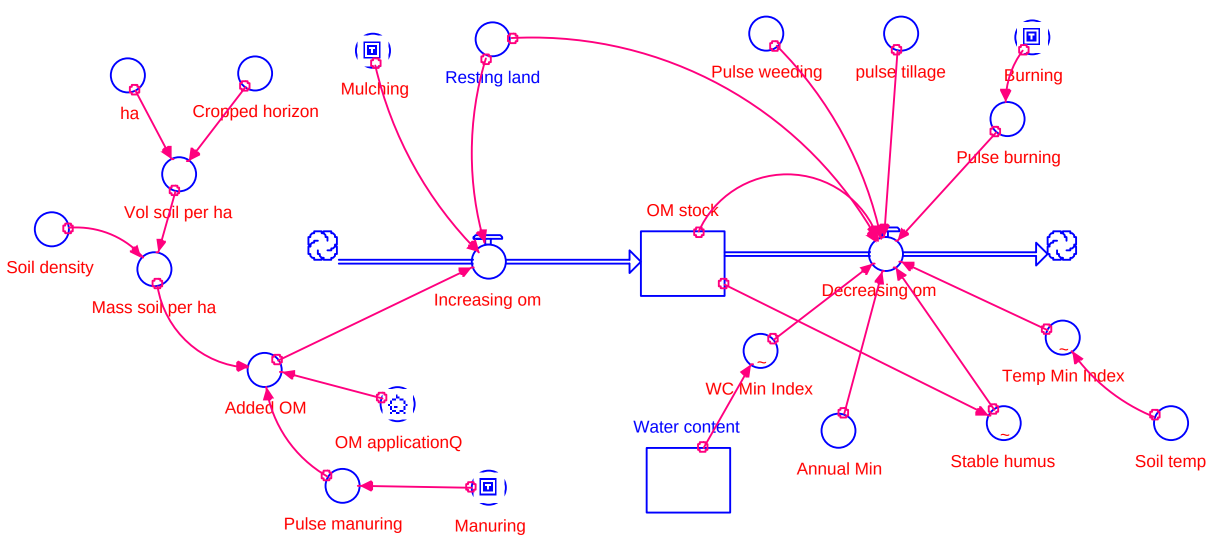


Figure 14 **Map describing the relationships in the sub-model on SOM -Stella®-**

Box 1
Equations and graphical relations for total SOM as state variable -Stella®-

```
OM_stock(t) = OM_stock(t - dt) + (Increasing_om - Decreasing_om) * dt
INIT OM_stock = 0.03

INFLOWS:
Increasing_om = if Resting_land>0 then 0.00001 else
if Mulching>0 then 0.00001+Added_OM else
Added_OM

OUTFLOWS:
Decreasing_om = if Resting_land>0 then (OM_stock*(1-Stable_humus)*Temp_Min_Index*(Annual_Min/365)*WC_Min_Index) else
(OM_stock*Pulse_burning*0.01)+(OM_stock*pulse_tillage*0.02)+
(OM_stock*Pulse_weeding*0.01)+(OM_stock*(1-Stable_humus)*Temp_Min_Index*(Annual_Min/365)*WC_Min_Index)
Added_OM = if Pulse_manuring>0 then
(OM_applicationQ*0.95*0.6)/Mass_soil_per_ha else 0

Annual_Min = 0.5
Burning = 1
Cropped_horizon = 0.2
ha = 10000
Manuring = 1
Mass_soil_per_ha = Soil_density*Vol_soil_per_ha
Mulching = 1
OM_applicationQ = 10000
Pulse_burning = if Burning>0 then
pulse(1,258,365) else 0
Pulse_manuring = if Manuring>0 then
pulse(1,274,365) else 0
pulse_tillage = pulse(1,265,365)
Soil_density = 1300
Vol_soil_per_ha = Cropped_horizon*ha
Stable_humus = GRAPH(OM_stock)
(0.00, 1.00), (0.01, 0.99), (0.02, 0.9), (0.03, 0.8), (0.04, 0.7), (0.05, 0.6), (0.06, 0.5), (0.07, 0.42), (0.08, 0.37), (0.09, 0.33), (0.1, 0.3)
Temp_Min_Index = GRAPH(Soil_temp)
(10.0, 0.00), (11.6, 0.065), (13.2, 0.16), (14.7, 0.33), (16.3, 0.545), (17.9, 0.75), (19.5, 0.915), (21.1, 0.985), (22.6, 1.00), (24.2, 1.00),
(25.8, 1.00), (27.4, 1.00), (28.9, 1.00), (30.5, 1.00), (32.1, 1.00), (33.7, 1.00), (35.3, 1.00), (36.8, 1.00), (38.4, 1.00), (40.0, 1.00)
WC_Min_Index = GRAPH(Water_content)
(0.00, 0.00), (3.16, 0.04), (6.32, 0.26), (9.47, 0.6), (12.6, 0.865), (15.8, 0.97), (18.9, 1.00), (22.1, 1.00), (25.3, 1.00), (28.4, 1.00), (31.6,
0.995), (34.7, 0.96), (37.9, 0.885), (41.1, 0.75), (44.2, 0.525), (47.4, 0.255), (50.5, 0.085), (53.7, 0.025), (56.8, 0.00), (60.0, 0.00)
```

5.3.3 Dynamics of nitrogen

According to the literature both P and N are deficient in these soils (see Section 4). Although P is lost through erosion and therefore would ideally be considered, nothing is known about this relationship. Given some information – albeit limited - N was selected for modeling purposes. Thus, a second sub-model addresses the dynamics of nitrogen (see Figure 15) was developed. Table 8 shows the control variables impacting upon N content, while Box 2 displays more details in relations between variables.
Although some contradictions and knowledge gaps do persist in the literature (especially on *Colocasia*, in Southern African context), the model strives to draw from literature (as seen in previous section; Morel, 1989; Bonneau, 1979}) and to represent trends in accumulation or decrease in the two major forms of soil nitrogen (i.e. cation NH_4 and anion NO_3). It stresses the effects of selected discrete cropping practices or continuous processes such as soil water dynamics, as indicated below. The model does not consider the full actual complexity of interrelated processes underlying N dynamics. It tries to capture the main relations only (for instance, some interactions or processes, although demonstrated, are not considered – temperature on microbial activities of nitri-denitrification, water content on ammonization, atmospheric N_2 fixation, and the like).

In agro-ecosystems such as Craigieburn wetlands, the main mineral forms of N (i.e. NH_4 and NO_3, - those absorbed by plants) mostly derive from dead parts of natural vegetation or crops returning to the soil and decomposing, from quasi-instant yet limited release of mineral N when manure is spread, and from the decomposition and mineralization of SOM.

NO_3 is more mobile, soluble and easily leached with drainage and surface run-off (hence more volatile, and more difficult to monitor), while NH_4 derives from SOM and can be strongly bonded with clays. Both elements are assumed to be absorbed by *Colocasia* roots as sources of N (80% NO_3 as being more soluble, mobile and available in wet environments, and only 20% NH_4). Volatilization-denitrification refers to the overall loss in soil mineral NO_3 reduced into gas N_2 and N_2O and released into the atmosphere. Ammonization refers to the oxidation of NH_4 in gaseous ammonia NH_3 and its release into the atmosphere. Cropping practices that disturb topsoil increase ammonization and volatilization. Higher soil temperature has a similar effect.

Nitrification refers to the active microbial oxidation of NH_4 into NO_3. Denitrification (loss of NO_3) also refers to the transformation back into NH_4. but is not considered in the model since it seems to be a minor process only occurring significantly under long-term marked anaerobic conditions. All these processes are highly dependent on the availability of oxygen in the soil, therefore on water saturation of wetlands. High water content (=lower oxygen) favors volatilization and denitrification, while low water content favors nitrification. The two key state variables are **NH_4 content** and **NO_3 content**, both in kg/ha. They are combined as **total mineral N content**. Initial values, respectively 700 and 100 kg/ha/a., are quite similar to other tuber / corm crops. With no available data, it was assumed that the uptake would take place evenly over the 181 days of the crop cycle (although it was noted that both young plants and mature madumbes need less) and that 80% should come from NO_3 and 20% from NH_4 captured in the rhizosphere. A number of control variables impact upon them, as detailed in Table 8.

Table 8
Description of control variables and processes impacting upon mineral nitrogen content

Control variables	Effect	Description of effect	Specifications	Range / unit
Manure application	0 / + (NH_4) (NO_3)	Increasing NH_4 + NO_3 pools via direct release of mineral N when manure is spread	Pulse: once a year, October 1 (day #274) Dry matter content: 0.6 Total nitrogen mass content: 3% 5% of it immediately released (10% NO_3 + 90% NH_4)	0 to 45 kg/ha NO_3 + NH_4 (knob input device)
Crop demand	0 / - (NH_4) (NO_3)	Permanent decrease of both NH4 and NO_3 pools as absorbed by crops, unless water content reaches WP	Permanent Distributed over 365 days	100kg/ha/a (80% NO_3 + 20% NH_4)
Tillage	0 / - (NH_4) (NO_3)	Boost ammonization of NH_4 by 10kg/ha on the day it occurs Boost volatilization of NO_3 by 10kg/ha on the day it occurs	Pulse: once a year, September 22 (day #265) Dummy (off/on)	0 or 1 (switch) 0 to 20kg/ha/a
Weeding	0 / - (NH_4) (NO_3)	Boost ammonization of NH_4 by 5kg/ha on the day it occurs Boost volatilization of NO_3 by 5kg/ha on the day it occurs	Pulse: up to 4 times a year, Nov.15, Dec.15, Jan 15 and/or Feb.15 (days #319, 349, 15, 46) Dummy (off/on)	0 or 1 (switch) 0 to 40kg/ha/a
Burning	0 / - (NH_4) (NO_3)	Boost ammonization of NH_4 by 5kg/ha on the day it occurs Boost volatilization of NO_3 by 5kg/ha on the day it occurs	Pulse: once a year, September 15 (day #258) Dummy (off/on)	0 or 1 (switch) 0 to 10kg/ha/a
Resting of land	0 / -	Permanent decrease of both NH_4 and NO3 pools as absorbed by vegetation	Permanent over a chosen year Dummy (off/on)	0 or 1 (switch) 20kg/ha/a (50% NO3 +

				50% NH_4)
Mineralization of SOM	+ (NH_4) (NO_3)	Constant release of NO_3 (10%) + NH4 (90%) from 5% daily of the 0.03% N content of SOM	Permanent Varies according to SOM stock and mineralization rate (see SOM)	kg/ha about 500-600 kg/ha/a
Nitrification of NH4	- (NH_4) + (NO_3)	Constant increase of NO_3 from NH_4 pool (5.10^{-5} of it daily), affected by soil water content (as a proxy to O_2 availability)	Permanent, as a portion of NH_4	kg/ha about 20 kg/ha/a
Ammonization / volatilization of NH_4	- ($NH_4$4)	Constant loss of NH_4 into atmospheric NH_3 (1.10^{-4} of it daily), affected by soil temp., burning and tillage practices	Permanent as a portion of NH_4, with extra losses incurred upon cropping practices (see specs for those in table 1)	kg/ha about 15 to 50 kg/ha/a
Volatilization	- (NO_3)	Constant loss of NO_3 into atmospheric N_2 + N_2O(5.10^{-4} of it daily), affected by soil temperature, water content, burning and tillage practices	Permanent as a portion of NO_3 with extra losses incurred upon cropping practices (see specs for those in table 1)	kg/ha about 40 to 80 kg/ha/a
Leaching	- (NO_3)	Loss of NO_3 in soil water solution being washed away via drainage	Permanent but depends on drainage (see water sector). Only 50% of NO_3 is easily leached, and 3kg/ha remain linked to organo-mineral complex	kg/ha about 50 to 150 kg/ha/a

Box 2
Equations for total mineral N as state variable -Stella®-

```
NH4(t) = NH4(t - dt) + (refill - Plant_NH4_use - Nitrification - Ammonisation) * dt
INIT NH4 = 700

INFLOWS:
refill = if Pulse_manuring>0 then (OM_applicationQ*0.03*0.6*0.05*0.9) + Mineralization_flow*0.03*0.9*2600000 else
Mineralization_flow*0.03*2600000*0.9

OUTFLOWS:
Plant_NH4_use = if Resting_land>0 then 10/365 else
if Water_content<20 then 0 else 20/365
Nitrification = NH4*0.0005*((70-Water_content)/Water_content)
Ammonisation = if Resting_land>0 then (NH4*0.0001)*(Soil_temp/35) else
(NH4*0.0001)*(Soil_temp/35) + (Pulse_burning*10) + (pulse_tillage*20) + (Pulse_weeding*10)

NO3(t) = NO3(t - dt) + (Nitrification + M_refill - Plant_NO3_use - Volat_Denit - Leaching) * dt
INIT NO3 = 50

INFLOWS:
Nitrification = NH4*0.0005*((70-Water_content)/Water_content)
M_refill = if Pulse_manuring>0 then (OM_applicationQ*0.05*0.6*0.05*0.1) + Mineralization_flow*0.05*0.1*2600000 else
Mineralization_flow*0.05*0.1*2600000

OUTFLOWS:
Plant_NO3_use = if Resting_land>0 then 10/365 else
if Water_content<20 then 0 else 80/365
Volat_Denit = if Resting_land>0 then NO3*0.0005*(Soil_temp/35)*(Water_content/60) else
NO3*0.0005*((Soil_temp/35)*(Water_content/60)) + (Pulse_burning*10)+ (pulse_tillage*20) + (Pulse_weeding*10)
Leaching = if NO3 < 3 then 0 else (Leachable_NO3/NO3)*drainage*10000*0.0001

Total_leached(t) = Total_leached(t - dt) + (Leaching) * dt
INIT Total_leached = 0
INFLOWS:
Leaching = if NO3 < 3 then 0 else (Leachable_NO3/NO3)*drainage*10000*0.0001

Total_volat(t) = Total_volat(t - dt) + (Volat_Denit) * dt
INIT Total_volat = 0
INFLOWS:
Volat_Denit = if Resting_land>0 then NO3*0.0005*(Soil_temp/35)*(Water_content/50) else
NO3*0.0005*((Soil_temp/35)*(Water_content/50)) + (Pulse_burning*10)+ (pulse_tillage*20) + (Pulse_weeding*10)
Leachable_NO3 = NO3*0.5
Total_N_mineral = NH4+NO3
```

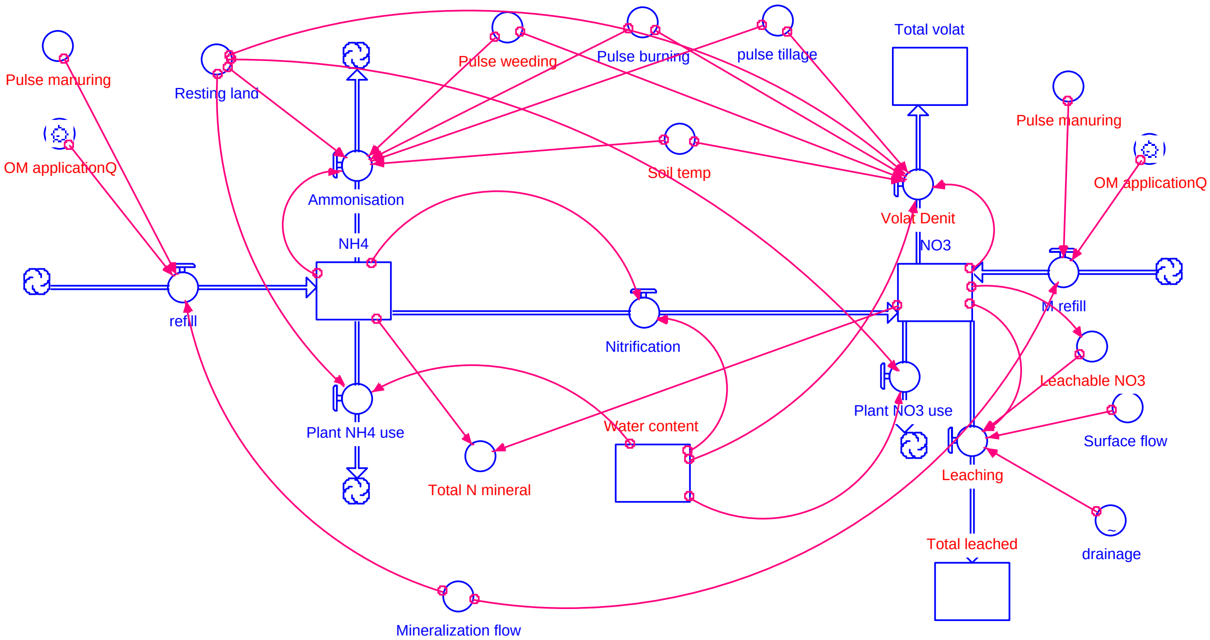


Figure 15 **Map describing relationships in N sub model –Stella®-**

5.3.4 Dynamics of soil structure

A third sub-model addresses the dynamics of soil structure (see Figure 16). Table 9 shows the control variables impacting upon SS, while Box 3 displays more details in relations between variables.

The key state variable is **soil structure** (as a volumetric index ranging between 0-100% of clustered particles, clods, crumbs and aggregates of more than 3mm diameter versus loose/ unstructured particles). The initial value is 50%. A number of control variables impact upon it, as given in Table 9.

It is assumed that soil organic matter content fuels soil macro fauna activity (e.g. earthworms) which is the main driver for soil structuration. Such activity stops when water content is low (earthworms migrate downwards or stop activity).

Yearly tillage, repeated weeding and burning all decrease soil structure through physical destruction of aggregates and clods.

Table 9
Description of control variables impacting upon soil structure as state variable

Control variables	Effect	Description of effect	Specifications	Range / unit
OM content	+	Increase proportionally by 1% structure per 1% OM content annually (if water content > 15% vol.)	Permanent Depending on OM content and water content	Around 3% mass
Tillage	0 / -	Decrease by **2**% structure on the day it occurs	Pulse: once a year, September 22 (day #265) Dummy (off/on)	0 or 1 (switch)
Weeding	0 / -	Decrease by **1**% structure on the day it occurs	Pulse: up to 4 times a year, Nov.15, Dec.15, Jan 15 and/or Feb.15 (days #319, 349, 15, 46) Dummy (off/on)	0 or 1 (switch)
Burning	0 / -	Decrease by **1**% structure on the day it occurs	Pulse: once a year, September 15 (day #258) Dummy (off/on)	0 or 1 (switch)
Resting of land	0 / -	Cancel tillage effect Increase by 2% per year, i.e. 0.0055 per day	Permanent Dummy (off/on)	0 or 1 (switch)

Box 3
Equations for soil structure as state variable -Stella®-

Soil_structure(t) **= Soil_structure(t - dt) + (Restore - Damage) * dt**
INIT Soil_structure = 50

INFLOWS:
Restore = if(Soil_structure>=100) then 0 else
if Water_content<15 then 0 else (OM_stock*100/365)
OUTFLOWS:
Damage = if Resting_land>0 then 0 else
(pulse_tillage*2)+(Pulse_weeding*1)+(Pulse_burning*1)

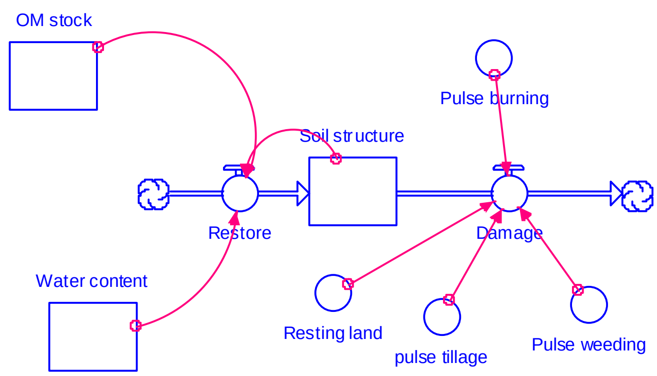


Figure 16 **Map describing relationships in the sub-model on soil structure dynamics –Stella®-**

5.3.5 Dynamics of soil temperature

A fourth sub-model addresses the dynamics of soil temperature (see Figure 17). Table 9 shows the control variables impacting upon SS, while Box 4 displays more details in relations between variables.

Soil temperature is considered a state variable (in degrees Celsius), which follows air temperature, according to a yearly cycle between 15 and 25°C. A number of control variables impact upon it, as explained in Table 10.

Table 10
Description of control variables impacting upon soil temperature as state variable

Control variables	Effect on state variable	Description of effect	Specifications	Range / unit
Air temperature	+/-	Soil temp = Air temp	Yearly cycle Soil temperature oscillates around air temp It is assumed that during rainy days (rain>0), rainfall drops by 20%	15-35 deg.C
Resting of land or Mulching	0 / -	Decreases variability and level of soil temp	Permanent Dummy (off/on)	0 or 1

Box 4
Equations for soil temperature as a state variable -Stella®-

Real_air_temp = if Rainfall_9598>0 then (Air_temp*0.8) else Air_temp
Soil_temp = if Mulching>0 then RANDOM(Real_air_temp-(Real_air_temp*0.05),(Real_air_temp+(Real_air_temp*0.05)))
else if Resting_land>0 then RANDOM(Real_air_temp-(Real_air_temp*0.05),(Real_air_temp+(Real_air_temp*0.05))) else
RANDOM(Real_air_temp-(Real_air_temp*0.1),(Real_air_temp+(Real_air_temp*0.3)))
Air_temp = GRAPH(TIME)
(not developed here in full for space-saving purpose)

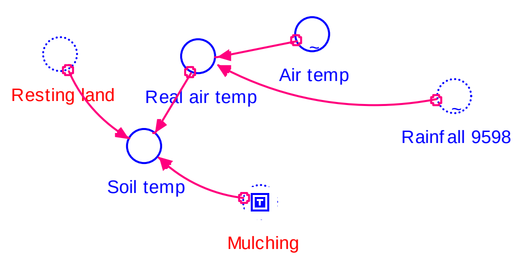


Figure 17 **Map describing the relationships in the sub-model on soil temperature dynamics -Stella®-**

5.3.6 Dynamics of water content

A fifth sub-model addresses the dynamics of water (WC) within the ridged beds (see Figure 18). Table 11 shows the control variables impacting upon WC, while Box 5 displays more details in relations between variables

The key state variable is **water content (WC)** (in mm within the 0.2m of topsoil). Its initial value is the field capacity (i.e. 60 mm). Several control variables impact upon it, as explained in Table 11.

In this sub-model, an important control variable is **field capacity (FP**, see Table 4**)**, which determines the maximum water content. Over the 0.2 m of soil that are considered, initial field capacity is set at 60 mm (30% volumetric water content, or 30 cm^3 water in 100 cm^3 soil). It may evolve slightly according to humus content. The **wilting point (WP**, see Table 4**)** is another factor that is bound to water content as below that low level of water content, most water dynamics and processes are very limited (e.g. crop water consumption, conductivity). It is set at 15 mm (7.5% volumetric water content, or 7.5 cm^3 water in 100 cm^3 soil).

The other key control variable is rainfall. Under heavy rainfall, water content may be temporarily exceed field capacity (overflow). In such instance, drainage takes place (vertical, and lateral towards furrows) (at 20 mm maximum per day beyond FC, 5 between 50-60 mm, 0 below 50 mm) and possibly runoff (overflow) if water exceeds drainage capacity. Drainage is impacted upon by bed and furrow management (i.e. blocking, orienting furrows and/or staggering beds set drainage at 15, 12 or 10 mm when respectively all combined, twined, or singled-applied).

The (vertical) contribution of groundwater from the water table and lateral contribution by water-filled furrows to the beds forms the **capillarity** contribution (in mm). Capillarity is set at 0.7mm as initial value (20mm per month), and can increase if beds are oriented perpendicular to the riverine water flow (plus 0.2mm), if they are staggered (plus 0.3mm), if farmers block furrows (plus 0.2mm). Such practices are considered to slow down water flow in between beds, to heighten water level and ultimately to favour lateral capillarity to the beds.

Crop demand is primarily determined by evaporative crop demand ETm (see Table 4). In the absence of accurate references regarding madumbes in the lowveld area, sweet potato ETm is used as a proxy. Between field capacity and 20 mm less than field capacity (i.e. when water is not a limiting production factor), the actual evapotranspiration ETa equals ETm[6]. Below, water stress applies and ETa decreases proportionally to water content. Capillarity also decreases with soil water content as it depends on conductivity.

Ultimately, a ratio ETa / ETm is calculated, indicating the level of water stress. For comparitive purposes between treatments / simulations, a mean water deficit was then calculated over the 4-year period.

Table 11
Description of control variables impacting upon water content as state variable

Control variables	Effect on state variable	Description of effect	Specifications	Range / unit
Rainfall	+	Increase, each precipitation considered efficient	Permanent Daily values over 4 years (1995-1998)	0-135mm
Field capacity	- / +	Forms the maximum capacity for water content	Permanent Impacted upon by humus content	+/- 60mm as initial value

[6] Although this may seem low the following comment pertains: Close to field capacity 60mm and 20mm below it (40mm), ETm equals potential climatic demand, hence a coefficient of 1. Then this coefficient decreases proportionally until permanent wilting point (15mm) is reached. Then vegetation cannot evaporate anymore (or marginally the soil still can). Hence the equation between WC 40mm and 15mm : ETm ratio = WC*0.04 - 0.6

Capillarity	+	Increase	Permanent Impacted upon by farmers' practices on ridged beds and by WC	0.7-1.4mm, 0.7mm as initial value
Crop demand ETa	-	Decrease	Permanent Daily values over 4 years Depending on cropping system (madumbe or natural vegetation) and on ETm	50-170mm
Mulching	+	Diminish Eta (soil evaporation) (90% ETa)	Permanent Dummy (off/on)	0 or 1
Drainage	-	Decrease WC if FC is near (vertical drainage + lateral drainage to furrows)	Depends on WC Impacted upon by bed / furrow management	0-20mm

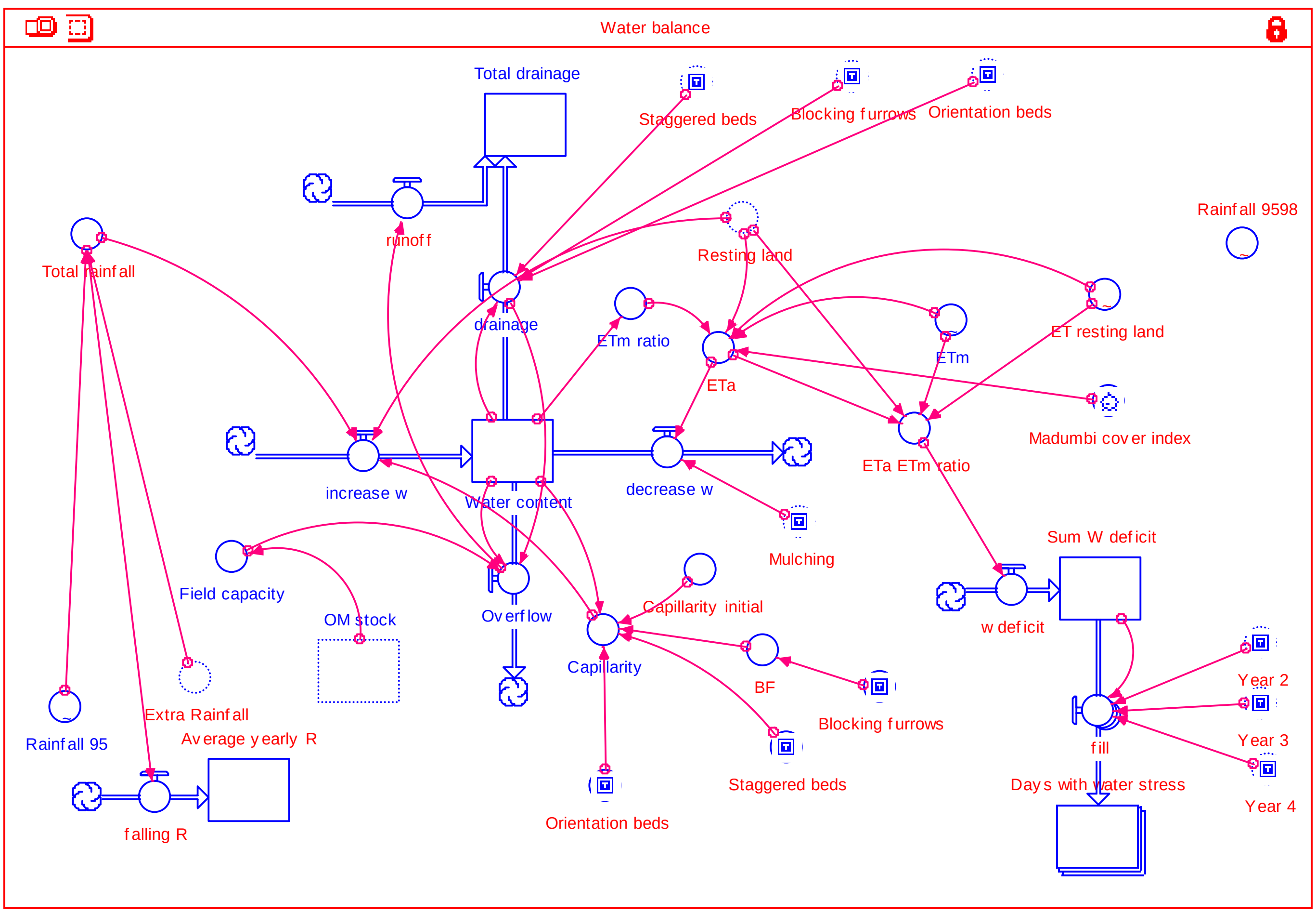


Figure 18 **Map describing the relationships in the sub model on water content dynamics - Stella®-**

Box 5
Equations for soil water content as a state variable -Stella®-

```
Average_yearly_R(t) = Average_yearly_R(t - dt) + (falling_R) * dt
INIT Average_yearly_R = 0

INFLOWS:
falling_R = Total_rainfall/4

Sum_W_deficit(t) = Sum_W_deficit(t - dt) + (w_deficit) * dt
INIT Sum_W_deficit = 0

INFLOWS:
w_deficit = if ETa_ETm_ratio>0.3 then 0 else
if ((time<91) or (time>273 and time<456) or (time>638 and time<821) or (time>1003 and time<1186) or (time>1368)) then 1 else 0

Total_drainage(t) = Total_drainage(t - dt) + (drainage + runoff) * dt
INIT Total_drainage = 0

INFLOWS:
drainage = if Water_content<50 then 0 else
if Water_content>60 then 20 else
(Water_content*2)-100
runoff = Overflow

Water_content(t) = Water_content(t - dt) + (increase_w - decrease_w - drainage - Overflow) * dt
INIT Water_content = Field_capacity

INFLOWS:
increase_w = Total_rainfall+Capillarity
OUTFLOWS:
decrease_w = if (Water_content<15) then (Water_content*0.06666) else
if Mulching>0 then (ETa*0.9) else ETa
drainage = if Water_content<50 then 0 else
if Water_content<60 then 5 else
if (Water_content>60 and Blocking_furrows+Orientation_beds+Staggered_beds=1) then 15 else
if (Water_content>60 and Blocking_furrows+Orientation_beds+Staggered_beds=2) then 12 else
if (Water_content>60 and Blocking_furrows+Orientation_beds+Staggered_beds=3) then 10 else
20
Overflow = if Water_content<=(Field_capacity+20) then 0 else
Water_content-Field_capacity-drainage
Blocking_furrows = 1
Capillarity = if Water_content<30 then (Capillarity_initial+(Staggered_beds*0.3)+(Orientation_beds*0.2)+(Blocking_furrows*0.2))*0.5
else
if Water_content<25 then (Capillarity_initial+(Staggered_beds*0.3)+(Orientation_beds*0.2)+(Blocking_furrows*0.2))*0.1 else
Capillarity_initial+(Staggered_beds*0.3)+(Orientation_beds*0.2)+(Blocking_furrows*0.2)

Capillarity_initial = 0.7
Days_with_water_stress = Sum_W_deficit/4
ETa = if Resting_land>0 then (ET_resting_land*ETm_ratio) else
if ((time>90 and time<274) or (time>455 and time<639) or (time>820 and time<1004) or (time>1185 and time<1369)) then
(ET_resting_land*ETm_ratio) else (ETm*ETm_ratio*Madumbe_cover_index)
ETa_ETm_ratio = if ETm=0 then 0 else ETa/ETm
ETm_ratio = if Water_content<15 then 0 else
if Water_content>40 then 1 else
(Water_content*0.04) - 0.6
Field_capacity = ((1000/3)*OM_stock) + 50
Madumbe_cover_index = 0
Orientation_beds = 0
Staggered_beds = 0
Total_rainfall = Extra_Rainfall+Rainfall_95
```

5.3.7 Dynamics of soil erosion

A fifth sub-model addresses the dynamics of **soil erosion** in the ridged beds (see Figure 19) - i.e. the loss of soil elements through runoff that occur upon the surface of ridges. Table 12 shows the control variables impacting upon soil loss, while Box 6 displays more details in relations between variables. Such a process favors soil loss in beds located in the upper part of the catchment, and soil accumulation in the lower section. It does not capture erosion processes that take place along the riverine stream or the furrows (see Section 5.3.1).

The quantity of water flowing (**overflow** or **runoff**) over the surface during heavy rainfall is the major control variable (see section on water dynamics). As a proxy for stream velocity, it first determines the **carrying capacity**, i.e. the load in soil that can be washed away with runoff (kg per mm or per liter). Below 5mm runoff (less than 5 liters/m^2/day), it is deemed to be unable to displace soil elements (a proxy for velocity). Above 5mm, it increases proportionally up to 50g per liter when runoff is 30mm, then stabilizes at that level beyond 30mm. Carrying capacity may slightly increase if the **soil structure** is poor (<50%), and increase significantly when the soil is loose (exponential relation) or slightly decrease if structure is above 50%. Also, cropping practices generate soil disturbances which increase the erosion risk (**erosion risk factor**), as follows:

- for 10 days following planting or tillage / bed preparation, risk factor is 1,
- for 5 days following weeding (if any), risk factor is 1,
- other days under cropping incur a risk factor varying from 0.2 to 1. Ultimate production of a given cycle is used as a proxy to crop cover and rooting that protects from erosion, as production varies from full potential (3kg per m^2) to lower values, the risk factor varies accordingly from 0.2 to 1 (low production, hence low soil protection)
- if mulching is applied, the risk factor is 0.1,
- if land is rested (natural vegetation and weeds), the risk factor is 0.05.

Box 6
Equations for erosion as a state variable -Stella®-

```
Soil_loss(t) = Soil_loss(t - dt) + (Soil_displaced) * dt
INIT Soil_loss = 0

INFLOWS:
Soil_displaced = if Overflow<5 then 0 else
if Overflow>30 then 0.05*Overflow*(Soil_struct_factor)*RF_real*10000 else
((Overflow*0.0008)-0.004)*Overflow*(Soil_struct_factor)*RF_real*10000
Average_yearly_soil_loss = Soil_loss/4
EF_dec = if Dec>0 and
((time>348 and time<354) or (time>713 and time<719) or
(time>1078 and time<1084) or (time>1443 and time<1449))
then 10 else 1
EF_feb = if Feb>0 and
((time>45 and time<51) or (time>410 and time<416) or
(time>775 and time<781) or (time>1140 and time<1146))
then 10 else 1
EF_jan = if Jan>0 and
((time>14 and time<20) or (time>379 and time<385) or
(time>744 and time<750) or (time>1109 and time<1115))
then 10 else 1
EF_nov = if Nov>0 and
((time>318 and time<324) or (time>683 and time<689) or
(time>1048 and time<1054) or (time>1413 and time<1419))
then 10 else 1
EF_tillage_plant = if (time>88 and time<99) or
(time>264 and time<275) or
(time>453 and time<464) or
(time>629 and time<640) or
(time>818 and time<829) or
(time>994 and time<1005) or
(time>1183 and time<1194) or
(time>1359 and time<1370) then 10 else 1
RF_real = if Resting_land>0 then 0.1 else
if Mulching>0 then 0.2 else
if Risk_factor>10 then 1 else 0.4
Risk_factor = EF_dec+EF_feb+EF_jan+EF_nov+EF_tillage_plant
Soil_struct_factor = 9.9806*EXP(-0.0466*Soil_structure)
```

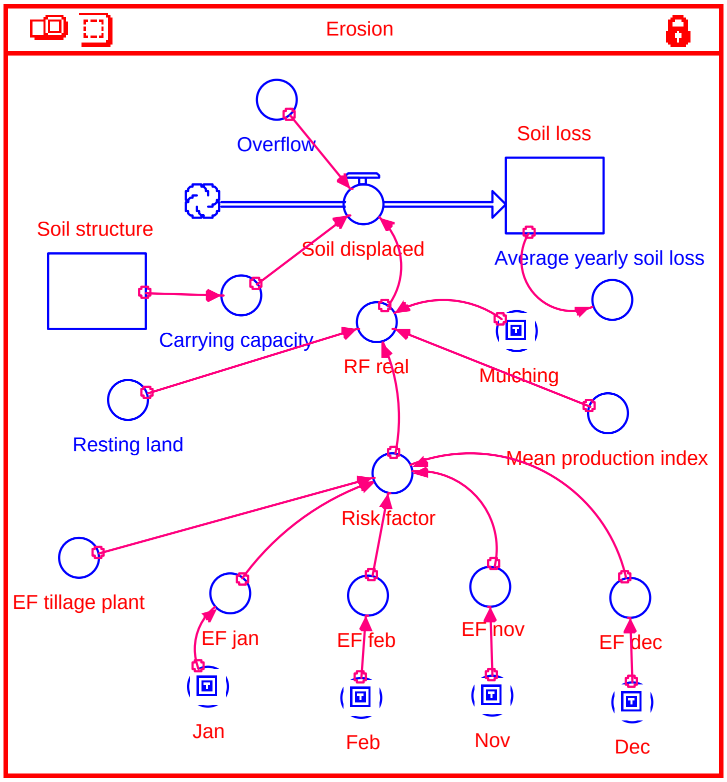


Figure 19 **Map describing the relationships in the sub-model on soil erosion dynamics - Stella®-**

Table 12
Description of control variables impacting upon soil loss as state variable

Control variables:	Effect on state variable	Description of effect	Specifications	Range / unit
Overflow	+	Increase soil loss when >5mm	Permanent Daily values over 4 years (1995-1998) Depending on water balance	0-about 40mm
Carrying capacity	+	Set at 20g of soil carried by each liter overflowing. May vary according to soil structure	Permanent Impacted upon by soil structure	15-25 g/l
Erosion risk factor	0 / -	May limit erosion depending on soil surface status and practices	Permanent Impacted upon by mulching, resting, production, tillage, planting, harvesting and weeding	0.05-1

5.4 Results

A summary of all results is presented in Table 13.

5.4.1 Bed management

Scenario 1.1: Scenario 0+ Beds are oriented perpendicular to main stream flow

Under this scenario, organic matter content decreases over the 4 years, then stabilises in the long run. It is likely that the SOM decline is due to the soil water content being kept high by the capillarity effect of water in the perpendicularly-orientated furrows. This high water content causes high SOM conversion and mineralisation (if water contents stays between 15 and 30%). However, a realistic representation of the feedback from crop production to SOM is missing from the model. Since the water content is elevated, crop production should be high and so more SOM will be generated (further discussed under Section 5.5). Soil surface erosion is 5.5 t/ha/a, slightly less than under the baseline conditions[7]. Crop production is low due to the loss of N.

It seems that increased water supply to beds from furrow water lateral favors saturation and runoff at times of heavy rainfall, hence some more soil loss. However, crop cover will probably mitigate this as it is a most effective erosion decreasing parameters. Moreover, the decrease in velocity in the furrows afforded by the orientation will reduce loss of sediments to scour (in addition to bed surface erosion).

Ultimately production decreases (as does income) probably due to the loss of N. The decrease of N can result through: (1) the loss of SOM (although the rate of mineralization may be higher (between WC 15-30%), or (2) through wash off in runoff (although again, increased cover should limit wash off).

Scenario 1.2 (a) and (b): Scenario 0+ (a) furrows are blocked during low flows and (b) beds are staggered (water flows much slower in between beds and level of water increases).

Under both scenarios, organic matter content decreases over the 4 years. This is probably because the longer period of higher water content (specifically between 15 and 30%) will increase mineralization. Soil surface erosion is slightly more than under previous scenarios when furrows are blocked and higher under staggered beds. Again, increased water supply to beds from furrow water lateral favors saturation and runoff at times of heavy rainfall, hence potential soil loss. However, as stated in the previous scenario, crop cover would tend ameliorate this. Production decreases significantly (from the 2nd cycle), on account of increased N deficiency, due to wash off, as described for the previous scenario.

Scenario 1.3 (a) and (b): Scenario 1.2(b) + manure (a) 4 kg fresh manure per m^2 and (b) (2 kg fresh manure per m^2)

Organic matter content increases regularly over the 4 years but only under the application of 4 kg fresh manure/m^2. Soil structure increases slightly with both doses. Soil surface erosion is low at between 5.8 and 6.5 t/ha/a for scenarios 1.3 (a) and (b) respectively. Production increases regularly, on account of improved water balance and correction of N leaching through manuring.

Several tests showed that below 4 kg/m^2, the positive effect shows only after 1 or 2 cycles. In order to benefit immediately from it, this amount is necessary. After a couple of cycles, a more limited dose may allow just maintaining N status and yield the same results.

[7] There will be more days where runoff exceeds 30 mm and takes off the 50 g/l/day.

5.4.2 Effects of mulching, resting and manuring

<u>Scenario 2.1 (a) and (b)</u>: Scenario 0 + (a) mulching + (b) storm event in December

Under scenario 2.1(a), organic matter content remains stable over the 4 years. Soil structure slightly increases. Soil surface erosion is low at 1.7 t/ha/a. Indeed, mulching has the highest impact on reducing erosion.

Production is fairly high (468-520-520 kg per household), on account of improved water and N balance. As a single practice, mulching proves to be the most efficient measure for improving soil and production in ridged beds. A storm event appears to have little impact other than an increase in erosion to 3.4 t/ha/a but this remains below the baseline value.

<u>Scenarios 2.2 (a) and (b):</u> Scenario 0 + (a) 0.5 kg dose of fresh manure/m^2 + (b) mulching

This set of scenarios aims at assessing the effect of different dose of manure applied at planting and mulching.

Results show that small doses (such as 0.5 kg/m^2) have very limited impact, in comparison to no application. As seen in previous scenarios (1.3), positive effects require larger doses (increase SOM and N) and large amounts of manure application appear to be necessary initially. Production remains as for the baseline scenario.

However, combining small doses of manure and mulching appear to have a marked improvement on SOM, N, water stress and hence production which is then fairly high (468-520-520 kg per household), As above (2.1), erosion decreases significantly with mulching to 1.7 t/ha/a.

<u>Scenario 2.3</u>: Scenario 0 + resting of land in year 3 (no cropping in second full cropping season)

This scenario aims to assess the effect of resting land in between crop cycles. Results show that resting land improves soil structure. However, natural vegetation tends to dry up the soil more efficiently than madumbes, therefore there is a slight increase in water stress during the crop cycle that follows. Obviously there is no production when land is rested. All in all, resting land certain years may have a very positive effect on soil restoration, and maintaining following yields at good levels in the absence of any other measure.

5.4.3 Effects of aggressive practices (weeding and burning)

<u>Scenario 3.1</u>: Scenario 0 + burning all surface vegetation before tillage/preparation, on Sept. 15.

Under scenario 3.1, all variables compare with the baseline scenario. Production compares with that of no burning. All in all, yearly burning does not have a major impact in the short term.

<u>Scenario 3.2</u>. Scenario 0 + weeding in December

One weeding (removal of invasive weeds over beds by hoeing) in December 15 has little effect.

<u>Scenario 3.3 (a) and (b):</u> Scenario 0 + (a) weeding in January and (b) rainfall event in January

One weeding in January 15 has a more marked effect on erosion which increases to between (a) 10 t/ha/a and (b) 13.5 t/ha/a. This emphasizes the risk incurred when weeding (or any soil disturbance) synchronizes with (a) low plant cover from immature crops, compounded by (b) heavy rainfall. Moreover the effect on erosion is probably compounded by the antecedent moisture conditions, since with greater soil moisture with the onset of the rainy season, the water table is likely to be closer to surface, resulting in greater partitioning of rainfall to overland flow.

Single weeding has no other impact on production which remains at the baseline levels.

Scenario 3.4 (a) and (b): Scenario 0 + (a) weeding in November, December, January, February and (b) burning and (c) plus rainfall event in November

In order to maintain beds and avoid competition with madumbe, farmers may weed every month. Such scenario increases significantly erosion, which increases to about 12 t/ha/a. This nearly doubles to a peak value of 21 t/ha/a if there is a rainfall event in November (i.e. when fields are cleared and weeded).

Interestingly, all other outputs remain the same as under current conditions.

5.4.4 Permanent resting of land

Scenario 4.1

Permanent resting of land means returning to fallow land, and then to natural vegetation, with no cropping over the 4-year period.

If land is rested throughout the 4 years, no production is considered. Organic matter content is stable with a slight increase in the long run and soil structure increases significantly. Soil surface erosion is minimal, at 0.66 t/ha/a.

The introduction of exceptional winter rainfall does not change the figures, whichever month applies. Introduction of exceptional summer rainfall generate the following changes in average yearly soil loss: Oct.: 1.37 t/ha; Nov.:1.76; Dec.: 1.36; Jan.: 1.25; Feb.: 1.78; Mar.: 1.29.

5.4.6 Summary

The following preliminary conclusions can be drawn from the modeling exercise.

- The most significant impact on erosion (i.e. reduction in erosion) and water stress appears to be achieved through mulching, and crop/vegetational cover, and to a lesser extent through the application of manure.
- Unsurprisingly, erosion increases markedly when the clearing of land is syncrohnised with rainfall events (such as in November). This includes clearing due to weeding – an important issue to be considered by the *farmers support programme*. In other words, if weeding is not combined with mulching, the disadvantages (extremely high erosion) far outweigh the benefits of weeding.
- What is less clear from the above results are the impacts of changed bed management (i.e. bed and furrow orientation and the blocking of furrows). This is thought to reflect limits to the model and is further addressed in the discussion.
- Improvements in fertility and production are seen with the application of manure (4 kg/m^2), resting and mulching. However, the initial application of higher levels initially (4 kg/m^2) than those that are currently reported in Craigieburn appears to be quite important.
- Thus overall, it appears that based on our current understanding of relationships in Craigieburn wetlands, the application of manure, attention to mulching and resting of land – if possible – are likely to have the biggest positive impacts.

- Unsurprisingly, taking the field out of production for the 4-year period has a strong mitigatory effect. However, in the absence of any other measure resting land certain years may have a very positive effect on soil restoration, and maintaining following yields at good levels.

5.5 Discussion

A number of objectives underscored this work and the discussions are considered in light of these. Firstly, we sought to harness the existing information of the Craigieburn wetlands into a meaningful, integrated representation of the situation in the wetlands under different landuse practices. The underlying purpose was to investigate - via simulation - the risks associated with different practices given that real-life experimentation is ethically questionable when dealing with vulnerable peoples' livelihoods. Nonetheless it is well-recognised that models are only as good as their data, and even in the case of simulations, an assessment of their tractability and validity is still an important exercise prior to community feedback. An important part of this process – that of integration across disciplines – also merits discussion.

In assessing the scenario outcomes, one needs to consider the quality of the data before drawing definitive conclusions. It was pointed out earlier that despite the substantial body of work in Craigieburn wetland, there still exists a dearth of data of the type needed for meaningful input to dynamic modeling. Thus for example, an initial SOM value was set at 3% which was based on values from elsewhere rather than field measurements. Likewise the quantity of manure that is used is not known so an initial figure of 5 kg/m^2 (not particularly high in farming intensification projects) was used initially but later reduced on the basis that specialist felt it was a rather high. Equally, although linkages had been established by earlier research, (see for example Figure 8), little is known about the **relationships** between these variables. Thus for example, whilst SOM affects soil structure, as shown in the same figure, the nature of this relationship is not understood and had to be estimated. Again, in the absence of accurate references regarding crop demand by madumbes in the lowveld area, that of sweet potatoes had to be used as a proxy. A similar project examining the Sand River Catchment as a socio-ecological system also found that a major analytical constraint was the poor understanding of the relationships between variables (Pollard & Biggs, in prep.). Further research gaps are highlighted below.

In addition, the behaviour of certain variables and factors is still not well-understood. A case in point was the limitations on assessing bed management practices due to the lack of data on furrow hydraulics and the relationship to various practices (blocking, orientation, staggering). This was disappointing given that, to our knowledge, no other initiative examining the sustainable use wetlands has explored the importance of these management practices in terms of wetland health. Whilst this work attempted to do so, the outputs should be regarded with circumspection given that the relationship between furrows and beds and soil and water dynamics is poorly understood. However, a project that is currently underway should provide more information on the effects of hydraulics and water budget.

As stated, the results regarding the impacts of bed and furrow re-orientation and the blocking of furrows so as to retain water and reduce water velocities around plots are preliminary and should be treated judiciously. For example, we were unable to consider the impacts of furrow depth and bed height due to the aforementioned data constraints but theoretically, these would appear to be important aspects in the equation (and model). All in all, plot and furrow management requires further examination given the complex interactions between soil water content, plant cover and soil structure. Over certain water contents (estimated over a range of between 15-30%) water content can provide a cohesive capability to the soils. Wetter than this, the sediments wash off more readily, and drier materials are more easily dislodged. So moisture content has a counter active effect of stimulating more runoff, but also of binding the soil. Also since the scour effects of water discharge in furrows is not understood it has not been included in the current model. Finally, the feedback from good cover that would be afforded by crops (once mature) will mitigate erosion due to root binding and raindrop erosion has been included but requires refinement. Our understanding of the mechanisms of capillary action will be improved both with porous-media simulations based on measured soil characteristics as well as in-field observations.

Thus drawing any meaningful conclusion and hence advice to farmers with respect to bed and furrow management should be approached with caution. Certainly discussions regarding the control of water velocity and soil movement should include these aspects but without drawing any definitive conclusions at this stage.

Manure, fertility and yields

The results pertaining to improved yields and manure are commensurate with findings for other areas like Zimbabwe's eastern lowveld, which is also located on granites and has similar climatic and edaphic features to Craigieburn (see Section 4.2). As noted by various authors, although the cropping potential of wetlands in these landscapes are high, they are also typically low in N, P and S, as well as susceptible to nutrient deficiencies due to their acidity. Grant (1993) notes that for cropping systems to benefit from dambo (wetland) moisture, fertilizers or manure must be applied. Given the financial constraints for farmers and the ecological objectives of this project, improved manure application is the recommended approach. Grant (1993) also draws attention to the fact that the wetlands of these landscapes may also be deficient in micronutrients such as boron and zinc, which is commonly needed for maize on the granite sandveld soils.

The results regarding the importance of mulching agree with the evidence from other research that indicates increased yields associated with mulching. Indeed, trials in Hawaii suggest that the single most important factor that they examined on improved taro yields was mulching (e.g. {Miyasaka, 2001 #2425}.

Weeding

The risks incurred by weeding (or any soil disturbance) at a time that coincides with heavy rainfall are highlighted. This increases the erosion although a single weeding has no other impact on production. If however farmers weed every month in order to maintain beds and avoid competition with madumbes, erosion increases substantially. Here production declines to 1.5 t/ha/a - well below farmers desired target (30 t/ha/a) and yields reported for elsewhere (e.g. in Mbolongwane wetlands, the yield of madumbes was estimated 30 t/ha/a (Kotze, et al. 2002)).

The impact of spacing on taro yields has been reported in the literature but was not examined in this case. (Navarro and Misa 1985) reported that total yields increased significantly with decreased planting spacings. Lowest yields were obtained at 1.2 x 1.2 m spacing while the highest total yields were obtained at 0.6 x 0.6 m spacing. Authors also report that taro yields decline if grown on the same land in consecutive years (Takahashi 1984 in Asao et al. 2003).

Integration across disciplines

An important aspect of this work was to improve **integration** (of biophysical, social and economic data) so as to arrive at a meaningful – if incomplete – picture of the Craigieburn wetland. The process adopted here of constructing a 'straw-dog' model through Stella and using this as a basis for discussion and iteration amongst specialist was well-received. Firstly it encouraged specialist to think beyond their field of expertise and to draw linkages between certain variables and factors. It also served to highlight essential research required to build a more complete snapshot of reality. In an evaluation of the process, participants noted that it forced them to be more explicit about the linkages that they named. For example, the link between tillage and erosion is a commonly cited one but on examination (by asking the question 'how'?) the team agreed that it was actually linked via soil structure. Likewise being explicit about the links between mulching for example, and erosion (through SOM and soil structure in Figure 13) helped identify data needs and areas of uncertainty. Another important advance for the team was the recognition that although linkages had been established by earlier research, (see for example Figure 8), far less was known about the **relationships** between these variables. It also served to highlight essential research required to build a more complete snapshot of reality. Since learning and identification of knowledge gaps was an objective of this exercise, this has been achieved. In particular further research on hydrology and hydro-pedology is underway as well as on issues of governance and upland landuse practices.

The lack of a spatially explicit model together with limited data made a holistic examination of the wetland micro-catchment very difficult. Any future work that seeks to improve upon these results must recognise the need for (a) focused data collection of some of the key variables and their relationships and (b) a spatialised agent based-modeling platform. This would for example allow for an examination of the contributions from hillslopes (water, sediment, nutrients) and neighbouring wetland zones. This is important because wetland health – as defined in this work – is predicated on the soil and water balance (inflow and outflow). This would go some way to answering questions such as: what hillslope practices are there and therefore what are the impacts on the wetlands? The links are likely to be via sediment (S. Lorentz, personal observation). What change in practices in zones B and C either inhibit or contribute to sediment movement. This is also important because headcut erosion (moving up the streambed) was assumed to be stables in our modeling exercise. In reality, headcut erosion occurs when the accumulation of sediments in the stream channel leads to change in slope.

5.6 Conclusions

In section 5.1 it was stressed that certain practices are relatively easy for a farmer to implement whilst others would be much more difficult. The preliminary results indicate that it is worth focusing efforts on supporting changes in practices that are relatively easy to implement, namely mulching, blocking of furrows in the dry season and leaving portions of indigenous vegetation in the wetland. Erosion is heavily impacted upon by the lack of soil cover including weeding at inappropriate times such as when soils are exposed to rainfall at the start of the wet season. Ensuring good soil cover at the start of the rainy season is absolutely critical and relatively easily achieved through mulching and leaving crop cover.

Given the constraints of the modeling exercise discussed above (data, poorly understood relationships and so on), the positive impacts of the more difficult and labour intensive practices are not yet well-understood. Thus any major effort focusing on suggesting such changes (staggering of beds, the re-orientation of beds) should be judiciously and cautiously considered. We were unable to explore certain key issues through this exercise, and these require further examination. Nonetheless they represent innovative approaches to the wise use of wetlands and deserve further attention.

The lack of spatialisation within dynamic modeling makes it difficult to develop and test certain scenarios in any realistic and plausible way. The relationships between factors – or groups of factors – are influenced by their position in the landscape, so that for example, the impacts of sediment generation in Zone C may influence fertility development in Zone A. This problem associated with dynamic modeling is widely recognised and has led to the development of spatialised agent-based models. Such an undertaking was, however, beyond the bounds of the work reported herein. The spatial location of different elements in the landscape – requires agent-based modeling.

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Table 12 Summary of results for each scenario

Scenario	Trend in SOM	Trend in SS	Trend in N	Erosion (ton soil loss/ha/a)	Days with water stress each year	Days with NO3 stress	Production (kg/HH per cycle)	Daily calories (Kj/ capita) (*)	Yearly income from sales (R/ capita/a) (**)
0. Baseline: Current	-	0	-	5.63	19-12-12	0-0-0	364-455-455	296-403-403	252-343-343
1.1 [0 + beds perp. to flow]	-	0	-	5.53	10-5-5	0-0-18	480-528-315	432-489-238	368-416-203
1.2 (a) [0 + blocking furrow]	-	0		6.38	15-10-10	0-0-0	417-480-480	304-368-368	357-432-432
1.2 (b) [0 + beds staggered, furrows blocked]	-	0	--	10.73	4-3-3	0-38-46	534-164-126	496-60-15	423-51-13
1.3(a) [1.2 + 4kg manure]	+	+	+	5.87	4-3-2	0-0-0	534-539-543	496-502-507	423-428-431
1.3 (b) [1.2 + 2kg manure)	0	+	0	6.50	4-2-2	0-0-1	534-543-539	496-507-502	423-431-428
2.1(a) [0 +mulching]	0	+	+	1.72	11-6-6	0-0-0	468-520-520	418-480-480	356-408-408
2.1(b) [2.1a + Dec storm]	0	+		3.43	11-6-6	0-0-1	468-520-511	418-480-469	356-408-400
2.2(a) [0.5kg + manure]	-	0	-	5.45	19-12-12	0-0-0	364-455-455	296-403-403	252-343-343
2.2(b) [2.2 + mulching]	+	+	+	1.67	11-6-6	0-0-0	468-520-520	418-480-480	356-408-408
2.3 [0 + resting of land in yr.3]	0	+	-	4.67	19-0-30	0-0-0	364-0-243	296-0-153	252-0-130
3.1 [0 + burning before tillage]	-	0	-	5.95	19-12-12	0-0-0	364-455-455	296-403-403	252-343-343
3.2 [0 = weeding Dec.]	-	0	-	5.91	19-12-12	0-0-0	364-455-455	296-403-403	252-343-343
3.3(a) [0+ weeding Jan]	-	0	-	10.36	19-12-12	0-0-0	364-455-455	296-403-403	252-343-343
3.3(b) [0+ weeding + storm Jan]	-	0	--	13.48	15-10-10	0-0-32	417-480-159	357-432-53	304-368-45
3.4(a) [0 + weeding in Nov., Dec., Jan., Feb.]	-	--	-	11.76	19-12-12	0-0-0	364-455-455	296-403-403	252-343-343
3.4(b) [3.4a + burning]	-	--	-	12.24	19-12-12	0-0-0	364-455-455	296-403-403	252-343-343
3.4 (c) [3.4(a)+(b) + Nov. storm]	-	--	--	21.02	19-12-12	0-0-0	364-455-455	296-403-403	252-343-343
4.1 Permanent resting	0	++	+	0.66					

(*) In case all production (less seed corms set aside) is self consumed
(**) In case all production (less seed corms set aside) is sold at market price
In trends: 0 indicates stability or marginal change; - / -- indicate slight or significant decrease; + / ++ indicate slight or significant increase
Note: trend in N includes NH4 and NO3, and consider rather long run evolution (after 4 years) than cyclical seasonal variations.