OVERSEER®

OVERSEER® Technical Manual

Technical Manual for the description of the OVERSEER® Nutrient Budgets engine

ISSN: 2253-461X

Characteristics of crops

June 2018

Prepared by D M Wheeler

AgResearch Ltd

Published by:

OVERSEER Management Services Limited

http://www.overseer.org.nz

The OVERSEER® owners are:

Ministry for Primary Industries (MPI), Fertiliser Association of New Zealand Inc. (FANZ) and AgResearch Ltd (AgResearch).

Preface

OVERSEER® Nutrient Budgets

OVERSEER® Nutrient Budgets (OVERSEER) is a strategic management tool that supports optimal nutrient use on farm for increased profitability and managing within environmental limits.

OVERSEER provides users with information to examine the impact of nutrient use and flows within a farm and off-farm losses of nutrients and greenhouse gases. An OVERSEER nutrient budget takes into account inputs and outputs and the key internal recycling of nutrients around the farm.

See the OVERSEER website for more detailed information: http://www.overseer.org.nz

This technical manual

OVERSEER is made up of a user interface and an engine. These two components work together to enable users to generate nutrient budget reports. The Technical Manual provides details of the calculation methods used in the OVERSEER engine

The OVERSEER engine is based on extensive published scientific research. Technical information about the model's development and use can be found in a growing number of conference proceedings and peer-reviewed papers. Given the ongoing upgrades many of the earlier papers no longer reflect the current version.

The Technical Manual chapters provide detailed descriptions of the methods used in the OVERSEER engine's main sub-models. The Technical Manual sets out the underlying principles and sources of data used to build the model engine. It is a description of the model as implemented, and hence references: may not now be the most appropriate or cover the range of data of information currently available, or may not necessarily be the most up to date. If the source of some information and/or assumptions is not known or could not be found, this is acknowledged.

The chapters will continually be updated to reflect the current version.

If readers have feedback or further technical information that they consider could contribute to the future development of the model, please provide feedback via the website http://www.overseer.org.nz.

Scientific contribution to model development:

OVERSEER is a farm systems model covering a wide range of science disciplines. Since the model's inception, a large number of researchers from many disciplines and organisations have contributed to its development.

Researchers contributing significantly to the crop characteristics described in this report include:

Hamish Brown, Plant and Food Research

Emmanuel Chakwizira, Plant and Food Research

Val Snow, AgResearch Ltd

Rogerio Cichota, AgResearch Ltd

David Wheeler, AgResearch Ltd

Contents

Characteristics of crops

1. Introduction

1.1. Crops

Crops are defined as plants that are grown following a cultivation, excluding pasture. They include crops defined as arable or cereal, vegetables, and crops grown specifically to feed to animals. The key focus of a crop is typically the yield of the product of the crop, such as grain or vegetable. Perennial crops such as fruit trees are covered separately.

Crops are included in fodder crop and cropping blocks. They are typically sown and managed within a rotation. The management of rotation is covered separately. This chapter defines the characteristics of individual crops sown in a rotation. These characteristics are used to generate input data for other sub-models. Examples of input data provided for other sub-models are (sub-models, data):

Crop rotation	Crop growth and residue characteristics.
Crop N model	Monthly N uptake.
Animal feeding	DM and ME, and nutrients.
Hydrology model	Crop cover.
Nutrient budgets	Product removal.

The management of irrigation and fertiliser is covered in the Hydrology and Characteristics of Fertiliser chapters respectively.

This chapter describes the characteristics of crops including the characteristics of the crops included (section 2), crop properties, parameters and nutrient contents associated with each crop that are stored in an internal database (section 3), and calculated properties such as the growth curve, cover, harvest index, yield and rooting depth (section 4), nutrient demand or uptake (section 5), and N fixation (section 6). This chapter then describes how these properties are estimated for those crops that can be defoliated prior to final harvest (section 7).

1.2. Workings of the technical manual

The aim of the technical manual is to provide a level of detail so that users of OVERSEER can clearly see the underlying principles and sources of data used to build the components of the model. This technical chapter is part of a series of technical manuals currently under development to explain the inner working of the OVERSEER engine.

In the equations in this manual, units are shown using ( ) and cross-references to other equations and sections within this manual or to other chapters of the technical manual are shown using [ ]. Equations with multiple '=' options are cascading alternatives in the order they are considered. The condition is shown on the right hand side. The variable and parameter names used are generally shortened names of the property. This naming convention is similar to the convention used in the OVERSEER engine model.

1.3. Abbreviations, chemical symbols and subscripts used

Abbreviations

CO_2	carbon dioxide.
DM	dry matter.
ME	metabolisable energy (megajoules, MJ).
m	metres

Chemical symbols

N, P, K, S, Ca, Mg, Na, and Cl refer to the nutrients nitrogen, phosphorus, potassium, sulphur, calcium, magnesium, sodium, and chlorine respectively. Chlorine and change in acidity (hydrogen or H+) are used interchangeably.

Subscripts

nut	nutrients.
mon	month since crop is sown unless specified otherwise

Within the code, month typically refers to the month of the rotation i.e. 1-24 (there are 24 months in a crop rotation).

2. Specifying crops

A crop is specified at time of sowing by the category (Table 1) and type of the crop (Table 2). The additional inputs required (Table 1) depend on the crop type.

2.1. Crop categories and inputs

Crop categories are used to group crops rather than have a long list, and to identify categories of crops between which the inputs or calculation methods differed. The inputs for each category in Table 1, the crop types in section 2.2, and the characteristics of non-vegetable crops are shown in 0.

Table 1. Crop categories and associated inputs.

Category	Category characteristics	Inputs at sowing[1]
Fodder crops	Fodder crops, typically grazed by animals.	• Yield or default can be used • Cultivation practice at sowing
Forages	Forage crops, typically grazed by animals. These are arbitrarily grass-like crops that typically regrow after defoliation.	• Yield or default can be used (except annual ryegrass) • Cultivation practice at sowing
Grain crops	Arable grain crops.	• Yield or default can be used • Cultivation practice at sowing • Residue disposal method at final harvest
Green manure	Green manures where no product is removed.	• Cultivation practice at sowing
Permanent pasture	Permanent pasture that is grazed, left to fallow, or defoliated.	• Cultivation practice at sowing • Grazed: animal source • Cut/carry have defoliations
Seed crops	Pasture seed crops.	• Yield or default can be used • Cultivation practice at sowing • Residue disposal method at final harvest
Vegetables: greens	Leafy green vegetables.	• Yield or default can be used • Cultivation practice at sowing • Residue disposal method at final harvest • For broccoli, Chinese cut can be selected
Vegetables: legumes	Vegetable crops that can fix nitrogen (beans, peas and lentils).	• Yield or default can be used • Cultivation practice at sowing • Residue disposal method at final harvest
Vegetables: root crops	Vegetable root crops.	• Yield or default can be used • Cultivation practice at sowing • Residue disposal method at final harvest
Vegetables: other	Other vegetable crops.	• Yield or default can be used • Cultivation practice at sowing • Residue disposal method at final harvest

1 Options for cultivation practice at sowing are 'Minimum till or spray first', 'Direct drilled', and 'Conventional'. Options for Residue disposal method at final harvest are ‘Retained’, ‘Burnt’, ‘Grazed’, and ‘Removed’. The typical yield of the crop (product removed) is displayed on the interface.

For all crops, soil test data at time of sowing can be entered. Typically these would be soil samples taken during the crop growing phase. However, those taken prior to sowing are acceptable provided no capital fertiliser has been applied. If no soil test data is entered (values are left as zero), default values as listed in Table 8 used.

2.2. Crop types

The crop types for each category are shown in Table 2.

Table 2. The general characteristics and crops for each crop category.

Category	Crops [1]
Fodder crops	Fodder beet
	Kale
	Rape
	Swedes
	Turnips bulb
	Turnips leafy
Forages	Annual ryegrass
	Forage barley (spring)
	Forage oats (spring)
	Forage oats (autumn)
	Maize silage
	Rye corn (spring)
	Rye corn (autumn)
	Triticale (spring)
	Triticale (autumn)
Grain crops	Barley (spring)
	Maize (short)
	Maize (medium)
	Maize (long)
	Oats (spring)
	Oats (autumn)
	Wheat (spring)
	Wheat (autumn)
Green manure	Brassica
	Lupins
	Mustard
	Oats and rye
	Phacelia
Permanent pasture	Grazed
	Fallow
	Cut/grazed
Seed crops	Clover seed
	Ryegrass seed
Vegetables: greens	Broccoli (winter/spring)
	Broccoli (summer)
	Brussel Sprouts
	Cabbage (winter/spring)
	Cabbage (summer)
	Cauliflower (winter/spring)

Category	Crops [1]
	Cauliflower(summer)
	Lettuce
	Spinach
Vegetables: legumes	Beans (green)
	Beans (dried)
	Lentils
	Peas (green)
	Peas (dried)
Vegetables: root crops	Kumara
	Potato (short)
	Potato (medium)
	Potato (long)
	Beets
	Carrots
	Parsnips
Vegetables: other	Onions
	Sweetcorn
	Squash
	Tomato

[1] Value in parenthesis is either the season of sowing (e.g., spring, autumn), the time to maturity (short, medium, long, with the length based on thermal time to reach maturity (see section 3.1.2, Table 5), or crop the purpose of the crop (green, dried) which also effects growth characteristics.

2.3. Non-vegetable crop characteristics.

The characteristics of non-vegetable crops are described in Table 3.

Table 3. The characteristics of non-vegetable crops.

Category	Category characteristics
Fodder crops	Fodder crops can have multiple defoliations by grazing or removal for feeding. No crop regrowth occurs after defoliation. Final harvest must be identified, and after final harvest, residues are retained.
Forages	Forage crops can have multiple defoliations by grazing or removal for feeding. For forage crops other than maize, the crop regrows after defoliation. The yield is the yield at the final defoliation. This is normally a silage cut. For maize, total harvest yield is a required input, and there is no regrowth if multiple defoliations are used. At the final harvest, the residues are retained. Annual ryegrass:

	Annual ryegrass can be defoliated (grazing or removal for silage or feeding), which is specified by the defoliation management option. Multiple defoliations are allowed, and these can be specifically to cover multiple months. If no defoliations are specified, DM accumulates to a maximum, and extra growth is returned to the soil as senesced material. Final harvest must be identified, and after final harvest, residues are retained.
Grain crops	The model allows defoliations (grazing or removal for silage or feeding) which are specified by the defoliation management option for autumn sown oats and wheat.
Green manure	All grown material is retained and added to the soil as residues. Thus there are no defoliations (grazing or removal) for silage or feeding.
Permanent pasture	Grazed pasture is automatically defoliated after a 3 month establishment phase as part of a normal grazing pattern. Specific defoliations are not specified. On fodder crops, it is assumed that pasture is grazed by farm animals. On crop blocks, the animal types grazing the pasture need to be specified. For defoliated pasture (cut or grazed), the time of defoliation is specified, and multiple defoliations can be specified. In all cases, if no defoliations are specified, DM accumulates to a maximum, and extra growth is returned to the soil as senesced material.
Seed crops	Crops grown for pasture seed production. Seed crops can be harvested for seed, or the vegetative growth can be defoliated (e.g., silage cut or grazed) multiple times. Residue management at harvest refers to management of the residue at seed harvest. Typically these crops are grown for 2 or 3 years, and the product (seed) harvested annually. Between and before harvests, the seed crop is defoliated by grazing or cut and carry. Multiple defoliations are allowed, and these can be specified to cover multiple months. After the first harvest, the crop is modelled similarly to pasture, and is referred to as **regrowth seed crops**.

2.4. Prior crops

The user selects crops prior to the start of the 2 year rotation. This is assumed to be permanent pasture for fodder crop blocks. For cropping blocks the prior crop options and equivalent crop type are as listed. The grain crop is modelled as a wheat crop, and the vegetable crop as a cabbage crop.

3. Crop properties

3.1. Values

3.1.1. Properties

Table 4 lists typical yield (T/ha), DM content (kg/kg), ME content (MJ ME/kg DM), the proportion of above ground yield that corresponds to root yield (proot), and maximum rooting depth (maxRD, m) for each crop. The source of the values is described in Table 9.

Product yield and typical yield is the yield of the product, and is on a wet or dry weight basis depending on how the crop is typically sold. The typical yield displayed on the interface as an indicator yield, and is used as a default yield when no yield is entered (section 4.3). For Chinese cut broccoli, typical yield is doubled.

DM and ME content apply to the crop product. DM content is used to estimate yield (section 4.3) and nutrient concentrations (section 5.1). Both DM and ME content are used to determine animal DM and ME intakes for crops that are grazed. The chapter Animal Intake shows where total values for DM, ME and nutrients from crops are used. The defoliation and allocation of crops to animal enterprises is not published.

The proportion of above ground yield that corresponds to root yield (proot) is used to estimate yield (section 4.3). Maximum rooting depth is used to estimate plant available water (Hydrology chapter).

Table 4. The typical yield (T/ha), DM content (kg/kg), ME content (MJ ME/kg DM), root yield as a proportion of above ground yield (proot), and maximum rooting depth (maxRD, m) for each crop.

	Typical yield	DM content	ME content	proots	maxRD
Fodder crops					
Fodder beet	8.5	0.17	12.5	0.1	1.5
Kale	12	0.16	12	0.3	1.2
Rape	6	0.1	12	0.3	1.2
Swedes	12	0.12	14	0.1	0.8
Turnips bulb	8	0.1	13	0.1	0.8
Turnips leafy	6	0.17	13	0.05	0.6
Forage crops					
Fodder beet	8.5	0.17	12.5	0.1	1.5
Kale	12	0.16	12	0.3	1.2
Rape	6	0.1	12	0.3	1.2
Swedes	12	0.12	14	0.1	0.8
Turnips bulb	8	0.1	13	0.1	0.8
Turnips leafy	6	0.17	13	0.05	0.6
Grain crops					
Barley (spring)	8	0.87	10.5	0.1	1
Maize (short)	12.2	0.87	10.5	0.1	1.5

	Typical yield	DM content	ME content	proots	maxRD
Maize (medium)	13.3	0.87	10.5	0.1	1.5
Maize (long)	13.5	0.87	10.5	0.1	1.5
Oats (spring)	4	0.87	10.5	0.1	1
Oats (autumn)	8	0.87	10.5	0.1	1.5
Wheat (spring)	8	0.87	10.5	0.1	1
Wheat (autumn)	11	0.87	10.5	0.1	1.5
Green manure					
Brassica	8	1	10.5	0.1	0.7
Lupins	12	1	10.5	0.1	0.7
Mustard	7	1	10.5	0.1	0.7
Oats and rye	10	1	10.5	0.1	1
Phacelia	5	1	10.5	0.1	0.7
Seed crops					
Clover seed	0.6	0.85	10.5	0.1	0.9
Ryegrass seed	1.5	0.85	10.5	0.1	0.7
Vegetables: greens					
Broccoli (winter/spring)	12	0.11	10.5	0.1	0.45
Broccoli (summer)	8	0.11	10.5	0.1	0.45
Brussel Sprouts	15	0.2	10.5	0.1	0.45
Cabbage (winter/spring)	50	0.12	10.5	0.1	0.45
Cabbage (summer)	70	0.08	10.5	0.1	0.45
Cauliflower (winter/spring)	30	0.1	10.5	0.1	0.45
Cauliflower(summer)	50	0.09	10.5	0.1	0.45
Lettuce	50	0.05	10.5	0.1	0.45
Spinach	22	0.05	10.5	0.1	0.45
Vegetables: legumes					
Beans (green)	8	0.21	10.5	0.1	0.7
Beans (dried)	3.5	0.86	10.5	0.1	0.7
Lentils	3.5	0.86	10.5	0.1	0.7
Peas (green)	8	0.21	10.5	0.1	0.7
Peas (dried)	3.5	0.86	10.5	0.1	0.7
Vegetables: root					
Kumara	50	0.226	10.5	0.1	0.5
Potato (short)	53	0.226	10.5	0.1	0.5
Potato (medium)	64	0.223	10.5	0.1	0.5
Potato (long)	71	0.216	10.5	0.1	0.5
Beets	55	0.14	10.5	0.1	0.5
Carrots	70	0.12	10.5	0.1	0.5
Parsnips	44	0.17	10.5	0.1	0.5
Vegetables: other					

	Typical yield	DM content	ME content	proots	maxRD
Onions	70	0.11	10.5	0.1	0.4
Sweetcorn	25	0.5	10.5	0.1	1
Squash	25	0.2	10.5	0.1	0.5
Tomato	100	0.05	10.5	0.1	0.5

3.1.2. Parameter values

Table 5 lists parameter values for each crop. The source of the values is described in 3.2. The derivation and use of these parameters are described in the following sections:

- Biomass coefficients (X_o_biomass, b_biomass) to estimate the proportion of maximum yield occurring in a given month (section 4.1).
- Harvest index coefficients (a_harvest, b_harvest) to estimate harvest index (section 4.2).
- Crop canopy cover coefficients (X_o_cover, a_cover, and b_cover) (section 4.4).
- The thermal time (°C month) when leaf area senescence begins (T_Senescence) and when the crop is mature (T_maturity) is used to estimate cover (section 4.4).

Table 5. Parameters used to estimate harvest index, crop canopy cover, maturity and biomass (see text for definitions).

	a_harvest	b_harvest	X_o_biomass	b_biomass	T_senesence	T_maturity	X_o_cover	b_cover	a_cover
Forage crops									
Annual ryegrass	0.1	0.00003	34	6.4	80	150	18	44	1
Forage barley (spring)	0.95	0	36	7.2	50	60	18	4	1
Forage oats (spring)	0.95	0	36	7.2	50	60	18	4	1
Forage oats (autumn)	0.95	0	61	13.3	80	100	18	4	1
Maize silage	0.95	0	54	11	75	120	32	6	0.85
Rye corn (spring)	0.95	0	36	7.2	50	60	18	4	1
Rye corn (autumn)	0.95	0	61	13.3	80	100	18	4	1
Triticale (spring)	0.95	0	36	7.2	50	60	18	4	1
Triticale (autumn)	0.95	0	61	13.3	80	100	18	4	1
Fodder crops									
Fodder beet	1	-0.000013	37.4	11.7	10000	10000	26.4	3.1	1
Kale	0.94	-0.00003	61.3	18	10000	10000	28.9	4.7	1
Rape	1	-0.000037	43.2	6.3	10000	10000	25.7	1.9	1
Swedes	0.99	-0.000013	37.4	11.7	10000	10000	26.4	3.1	1
Turnips bulb	1	-0.000016	42	7.4	10000	10000	25.3	1.5	1
Turnips leafy	1	-0.000085	45.6	11.3	10000	10000	28.1	2.8	1
Grain crops									
Barley (spring)	0.143	0.00004	36	7.2	50	60	18	4	1
Maize (short)	0.5	0	54	11	70	120	30	6	0.75
Maize (medium)	0.5	0	57	11	75	130	32	6	0.85
Maize (long)	0.5	0	60	11	80	140	35	6	0.92
Oats (spring)	0.143	0.00004	36	7.2	50	60	18	4	1
Oats (autumn)	0.0817	0.00003	61	13.3	80	100	18	4	1
Wheat (spring)	0.143	0.00004	36	7.2	50	60	18	4	1

	a_harvest	b_harvest	X_0_biomass	b_biomass	T_senesence	T_maturity	X_0_cover	b_cover	a_cover
Wheat (autumn)	0.0817	0.00003	61	13.3	80	100	18	4	1
Green manure									
Brassica	0	0	25	6	45	55	23	2	1
Lupins	0	0	25	6	45	55	23	2	1
Mustard	0	0	25	6	45	55	23	2	1
Oats and rye	0	0	36	7.2	50	60	18	4	1
Phacelia	0	0	25	6	45	55	23	2	1
Seed crops									
Clover seed	0	0.00015	30	10	110	120	25	4	0.8
Ryegrass seed	0	0.00007	30	10	75	90	18	4	1
Vegetables: greens									
Broccoli (winter/spring)	0.13	0	20	4	70	100	15	4	0.8
Broccoli (summer)	0.2	0	20	4	70	100	15	4	0.8
Brussel Sprouts	0.4	0	20	4	70	100	15	4	0.8
Cabbage (winter/spring)	0.6	0	18	3	70	100	12	4	0.8
Cabbage (summer)	0.75	0	18	3	70	100	12	4	0.8
Cauliflower (winter/spring)	0.3	0	20	4	70	100	15	4	0.8
Cauliflower(summer)	0.45	0	20	4	70	100	15	4	0.8
Lettuce	0.8	0	18	3	110	130	12	4	0.8
Spinach	0.7	0	18	3	70	100	12	4	0.8
Vegetables: legumes									
Beans (green)	0.45	0	25	6	45	55	23	2	0.8
Beans (dried)	0.5	0	25	6	45	55	23	2	1

	a_harvest	b_harvest	X_0_biomass	b_biomass	T_senesence	T_maturity	X_0_cover	b_cover	a_cover
Lentils	0.5	0	25	6	45	55	23	2	1
Peas (green)	0.45	0	25	6	45	55	23	2	1
Peas (dried)	0.5	0	25	6	45	55	23	2	1
Vegetables: root									
Kumara	0.84	0.000001	40	7	65	90	23	4	1
Potato (short)	0.84	0.000001	40	7	55	75	23	2	1
Potato (medium)	0.84	0.000001	45	9	65	85	23	2	1
Potato (long)	0.84	0.000001	50	11	75	95	23	2	1
Beets	0.76	0.000001	40	7	65	90	23	4	0.95
Carrots	0.83	0.000001	40	7	100	125	23	4	0.9
Parsnips	0.95	0.000001	40	7	65	90	23	4	0.95
Vegetables: other									
Onions	0.8	0	40	7	65	90	26	4	0.8
Sweetcorn	0.55	0	34	6.4	50	60	18	4	0.75
Squash	0.8	0	40	15	80	90	20	3	0.94
Tomato	0.5	0	40	7	65	90	23	4	1

3.1.3. Nutrient contents

The values of the nutrient contents for N (tops, stover and roots) are listed in Table 6. For other nutrients, the product and residual contents are listed in Table 6 and Table 7 respectively. The source of these values is described in section 3.2.

Table 6. Nutrient contents (%) of N for tops, stover and roots, and for product, nutrient contents of P, K, S, Ca, Mg, Na, and whether they are on a fresh (FW = 2) or dry weight (FDW = 1) basis.

	N root	N stover	N top	FDW	Product					
					P	K	S	Ca	Mg	Na
Forage crops										
Annual ryegrass	2	0.5	1.4	1	0.1	1.4	0.1	0.1	0.3	0.01
Forage barley (spring)	0.9	0.5	1.3	1	0.4	0.47	0.17	0.09	0.12	0.06
Forage oats (spring)	0.9	0.5	1.3	1	0.48	0.52	0.11	0.05	0.13	0.02
Forage oats (autumn)	0.9	0.5	1.3	1	0.48	0.52	0.11	0.05	0.13	0.02
Maize silage	0.7	0.7	1.4	1	0.33	0.6	0.06	0.18	0.16	0.14
Rye corn (spring)	0.9	0.5	1.3	1	0.48	0.52	0.11	0.05	0.13	0.02
Rye corn (autumn)	0.9	0.5	1.3	1	0.48	0.52	0.11	0.05	0.13	0.02
Triticale (spring)	0.9	0.5	1.3	1	0.48	0.52	0.11	0.05	0.13	0.02
Triticale (autumn)	0.9	0.5	1.3	1	0.48	0.52	0.11	0.05	0.13	0.02
Fodder crops										
Fodder beet	0.8	1.5	1.8	1	0.3	2.2	0.5	1.55	0.25	1.13
Kale	0.8	1	3	1	0.3	2.5	0.6	2.5	0.2	0.1
Rape	0.8	1	3	1	0.5	3.6	0.6	2.5	0.2	0.06
Swedes	0.8	0.6	2.5	1	0.3	2	0.5	1.5	0.25	0.25
Turnips bulb	0.8	0.6	2.5	1	0.4	3	0.6	1.5	0.15	0.2
Turnips leafy	0.8	1.5	3.5	1	0.4	3	0.5	2	0.2	0.2
Grain crops										
Barley (spring)	0.9	0.5	1.2	1	0.4	0.47	0.17	0.09	0.12	0.06

	N root	N stover	N top	FDW	Product					
					P	**K**	**S**	**Ca**	**Mg**	**Na**
Maize (short)	0.7	0.7	1.4	1	0.33	0.42	0.28	0.03	0.28	0.03
Maize (medium)	0.7	0.7	1.4	1	0.33	0.42	0.28	0.03	0.28	0.03
Maize (long)	0.7	0.7	1.4	1	0.33	0.42	0.28	0.03	0.28	0.03
Oats (spring)	0.9	0.5	1.2	1	0.48	0.39	0.21	0.08	0.13	0.06
Oats (autumn)	0.9	0.5	1.3	1	0.48	0.39	0.21	0.08	0.13	0.06
Wheat (spring)	0.9	0.5	1.3	1	0.48	0.52	0.11	0.05	0.13	0.02
Wheat (autumn)	0.9	0.5	1.3	1	0.48	0.52	0.11	0.05	0.13	0.02
Green manure										
Brassica	1	3	3	1	0.3	2	0.3	0.3	0.3	0.02
Lupins	1.5	3	3	1	0.3	2	0.3	0.3	0.3	0.02
Mustard	1	3	3	1	0.3	2	0.3	0.3	0.3	0.02
Oats and rye	0.9	0.5	1.2	1	0.3	2	0.3	0.3	0.3	0.02
Phacelia	1	3	3	1	0.3	2	0.3	0.3	0.3	0.02
Seed crops										
Clover seed	1	4	3.5	1	0.6	1.3	0.2	0.03	0.15	0.02
Ryegrass seed	1	1.5	1.5	1	0.4	0.8	0.3	0.2	0.16	0.01
Vegetables: greens										
Broccoli (winter/spring)	0.9	3.8	3.5	2	0.07	0.3	0.07	0.05	0.03	0.03
Broccoli (summer)	0.9	3.8	3.5	2	0.07	0.3	0.07	0.05	0.03	0.03
Brussel Sprouts	0.9	3.8	3.5	2	0.07	0.4	0.1	0.04	0.02	0.03
Cabbage (winter/spring)	0.9	3	2.6	1	0.26	2	0.11	0.35	0.11	0.09
Cabbage (summer)	0.9	3	2.6	1	0.26	2	0.11	0.35	0.11	0.09
Cauliflower (winter/spring)	0.9	3.8	3.5	2	0.07	0.3	0.08	0.03	0.02	0.03
Cauliflower(summer)	0.9	3.8	3.5	2	0.07	0.3	0.08	0.03	0.02	0.03
Lettuce	0.9	3	2.6	2	0.03	0.3	0.01	0.1	0.03	0.01

	N root	N stover	N top	FDW	Product					
					P	**K**	**S**	**Ca**	**Mg**	**Na**
Spinach	0.9	1.5	3	2	0.09	0.6	0.02	0.02	0.04	0.01
Vegetables: legumes										
Beans (green)	1.5	3	3.5	1	0.6	1.3	0.1	0.02	0.03	0.006
Beans (dried)	1.5	2	3.5	1	0.6	1.3	0.1	0.02	0.03	0.006
Lentils	1.5	2	3.5	1	0.4	0.7	0.25	0.1	0.1	0.01
Peas (green)	1.5	3	3.5	1	0.3	0.7	0.1	0.04	0.02	0.004
Peas (dried)	1.5	2	3.5	1	0.4	1	0.15	0.1	0.16	0.05
Vegetables: root										
Kumara	1	2	1.8	2	0.03	0.2	0.03	0.02	0.01	0.01
Potato (short)	1	2	1.8	1	0.3	2.17	0.09	0.2	0.1	0.09
Potato (medium)	1	2	1.8	1	0.3	2.17	0.09	0.2	0.1	0.09
Potato (long)	1	2	1.8	1	0.3	2.17	0.09	0.2	0.1	0.09
Beets	1	2	1.5	2	0.04	0.3	0.02	0.02	0.02	0.08
Carrots	1	2	1	1	0.35	2.8	0.12	0.04	0.02	0.104
Parsnips	1	2	1.35	2	0.04	0.3	0.02	0.04	0.03	0.01
Vegetables: other										
Onions	1	2	1.4	1	0.3	2	0.11	0.35	0.11	0.09
Sweetcorn	0.7	0.9	1.4	1	0.09	0.3	0.1	0.002	0.04	0.02
Squash	1	2	2	1	0.3	2.17	0.09	0.2	0.1	0.09
Tomato	1	2	2	2	0.02	0.3	0.03	0.01	0.01	0.01

Table 7. Nutrient contents (%) of residues for nutrients other than N.

	P	K	S	Ca	Mg	Na
Forage crops						
Annual ryegrass	0.1	1.4	0.1	0.1	0.3	0.01
Forage barley (spring)	0.04	1.4	0.14	0.3	0.08	0.05
Forage oats (spring)	0.08	1.35	0.13	0.18	0.08	0.14
Forage oats (autumn)	0.08	1.35	0.13	0.18	0.08	0.14
Maize silage	0.2	0.92	0.1	0.18	0.12	0.14
Rye corn (spring)	0.08	1.35	0.13	0.18	0.08	0.14
Rye corn (autumn)	0.08	1.35	0.13	0.18	0.08	0.14
Triticale (spring)	0.08	1.35	0.13	0.18	0.08	0.14
Triticale (autumn)	0.08	1.35	0.13	0.18	0.08	0.14
Fodder crops						
Fodder beet	0.15	1.5	0.25	0.28	0.15	0.25
Kale	0.15	2.2	0.4	1	0.2	0.3
Rape	0.15	3	0.4	1	0.2	0.1
Swedes	0.15	1.5	0.25	0.4	0.15	0.15
Turnips bulb	0.2	2	0.35	0.4	0.15	0.15
Turnips leafy	0.2	2	0.35	0.6	0.15	0.25
Grain crops						
Barley (spring)	0.04	1.4	0.14	0.3	0.08	0.05
Maize (short)	0.02	1.7	0.12	0.4	0.06	0.02
Maize (medium)	0.02	1.7	0.12	0.4	0.06	0.02
Maize (long)	0.02	1.7	0.12	0.4	0.06	0.02
Oats (spring)	0.06	2.3	0.11	0.14	0.05	0.05
Oats (autumn)	0.06	2.3	0.11	0.14	0.05	0.05
Wheat (spring)	0.08	1.35	0.13	0.18	0.08	0.14
Wheat (autumn)	0.08	1.35	0.13	0.18	0.08	0.14

	P	K	S	Ca	Mg	Na
Green manure						
Brassica	0	0	0	0	0	0
Lupins	0	0	0	0	0	0
Mustard	0	0	0	0	0	0
Oats and rye	0	0	0	0	0	0
Phacelia	0	1	0.25	0.3	0.3	0.05
Seed crops						
Clover seed	0.2	1.5	0.1	0.13	0.13	0.01
Ryegrass seed	0.1	1.4	0.1	0.1	0.3	0.01
Vegetables: greens						
Broccoli (winter/spring)	0.07	0.3	0.07	0.05	0.03	0.03
Broccoli (summer)	0.07	0.3	0.07	0.05	0.03	0.03
Brussel Sprouts	0.07	0.4	0.1	0.04	0.02	0.03
Cabbage (winter/spring)	0.26	2	0.11	0.35	0.11	0.09
Cabbage (summer)	0.26	2	0.11	0.35	0.11	0.09
Cauliflower (winter/spring)	0.07	0.3	0.08	0.03	0.02	0.03
Cauliflower(summer)	0.07	0.3	0.08	0.03	0.02	0.03
Lettuce	0.03	0.3	0.01	0.1	0.03	0.01
Spinach	0.09	0.6	0.02	0.02	0.04	0.01
Vegetables: legumes						
Beans (green)	0.01	0.3	0.1	0.1	0.02	0.01
Beans (dried)	0.01	0.3	0.1	0.1	0.02	0.01
Lentils	0.04	0.7	0.3	0.05	0.1	0.01
Peas (green)	0.1	0.7	0.1	0.1	0.02	0.01
Peas (dried)	0.1	0.7	0.1	0.1	0.02	0.01

	P	K	S	Ca	Mg	Na
Vegetables: root						
Kumara	0.03	0.2	0.03	0.02	0.01	0.01
Potato (short)	0.3	2.17	0.09	0.2	0.1	0.09
Potato (medium)	0.3	2.17	0.09	0.2	0.1	0.09
Potato (long)	0.3	2.17	0.09	0.2	0.1	0.09
Beets	0.04	0.3	0.02	0.02	0.02	0.08
Carrots	0.35	2.8	0.12	0.04	0.02	0.104
Parsnips	0.04	0.3	0.02	0.04	0.03	0.01
Vegetables: other						
Onions	0.3	2	0.11	0.35	0.11	0.09
Sweetcorn	0.09	1.2	0.1	0.01	0.06	0.02
Squash	0.6	5	0.6	4	1.1	0.1
Tomato	0.02	0.2	0.03	0.01	0.01	0.01

3.1.4. Typical soil tests values

Typical soil test values are arithmetic means obtained from aggregated data from soil samples submitted to a commercial lab between 1996 and 2001 (Wheeler *et al*. 2004). Values were used for the most similar crop where sued for crops where there was no data.

Table 8. Typical soil tests values for P, K, Ca and Mg.

	QT P	QT K	QT Ca	QT Mg
Fodder crops				
Fodder beet	35	7	9	17
Kale	35	7	9	17
Rape	35	7	9	17
Swedes	35	7	9	17
Turnips bulb	35	7	9	17

	QT P	QT K	QT Ca	QT Mg
Turnips leafy	35	7	9	17
Forage crops				
Annual ryegrass	-	-	-	-
Forage barley (spring)	30	12	21	36
Forage oats (spring)	18	8	8	21
Forage oats (autumn)	18	8	8	21
Maize silage	32	8	10	26
Rye corn (spring)	18	8	8	21
Rye corn (autumn)	18	8	8	21
Triticale (spring)	18	8	8	21
Triticale (autumn)	18	8	8	21
Grain crops				
Barley (spring)	30	12	21	36
Maize (short)	32	8	10	26
Maize (medium)	32	8	10	26
Maize (long)	32	8	10	26
Oats (spring)	24	8	10	21
Oats (autumn)	24	8	10	21
Wheat (spring)	18	8	8	21
Wheat (autumn)	18	8	8	21
Green manure				
Brassica	34	9	9	29
Lupins	34	9	9	29
Mustard	34	9	9	29
Oats and rye	34	9	9	29
Phacelia	34	9	9	29

	QT P	QT K	QT Ca	QT Mg
Seed crops				
Clover seed	27	17	8	31
Ryegrass seed	35	7	9	17
Vegetables: greens				
Broccoli (winter/spring)	26	16	9	21
Broccoli (summer)	26	16	9	21
Brussel Sprouts	34	9	9	29
Cabbage (winter/spring)	107	9	8	28
Cabbage (summer)	107	9	8	28
Cauliflower (winter/spring)	20	7	9	18
Cauliflower(summer)	20	7	9	18
Lettuce	99	16	13	22
Spinach	50	10	10	30
Vegetables: legumes				
Beans (green)	14	7	6	15
Beans (dried)	14	7	6	15
Lentils	14	7	6	15
Peas (green)	17	6	9	20
Peas (dried)	17	6	9	20
Vegetables: root				
Kumara	39	15	20	79
Potato (short)	28	9	9	21
Potato (medium)	28	9	9	21
Potato (long)	28	9	9	21
Beets	30	9	9	20

	QT P	QT K	QT Ca	QT Mg
Carrots	29	8	5	17
Parsnips	29	8	8	17
Vegetables: other				
Onions	33	9	12	29
Sweetcorn	30	9	11	26
Squash	34	11	13	41
Tomato	120	42	16	69

3.2. Source

Parameters for kale and turnips were derived from a range of sources as described by Chakwizira *et al*. (2011). Other fodder crops were based on expert opinion and literature reviews. The sources of data used for other crops are listed in Table 9.

Table 9. Source of crop coefficients

Parameter	Typical Yield	k_DM	a_HI	B_HI	Xo_Ndem	b_Ndem	N_Root	N_Shoot	N_Prod	P_Root	Max_RD	T_MaxRD	T_Sen	T_Mat	Xo_Cover	b_Cover	a_cover
Fodder crops	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit
Fodder beet	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit
Kale	Ch	Ch	Ch	Ch	Ca	Ch	Ch	Ch	Ch	Ch	Ch	Ch	Ch	Ch	Ch	Ch	Ch
Rape	Ch	Ch	Ch	Ch	Ch	Ch	Ch	Ch	Ch	Ch	Ch	Ch	Ch	Ch	Ch	Ch	Ch
Swedes	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit
Turnips bulb	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit
Turnips leafy	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit
Forage crops																	
Maize silage	Lit	Lit	Lit	Lit	Mai	Mai	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Mai	Mai	Mai
Barley (Spring)	Lit	Lit	Lit	Lit	Whe	Whe	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Whe	Whe	Whe
Triticale (Spring)	Lit	Lit	Lit	Lit	Whe	Whe	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Whe	Whe	Whe
Triticale (Autumn)	Lit	Lit	Lit	Lit	Whe	Whe	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Whe	Whe	Whe
Rye Corn (Spring)	Lit	Lit	Lit	Lit	Whe	Whe	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Whe	Whe	Whe
Rye Corn (Autumn)	Lit	Lit	Lit	Lit	Whe	Whe	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Whe	Whe	Whe
Oats (Spring)	Lit	Lit	Lit	Lit	Whe	Whe	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Whe	Whe	Whe
Oats (Autumn)	Lit	Lit	Lit	Lit	Whe	Whe	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Whe	Whe	Whe
Grain crops																	

Parameter	Typical Yield	k_DM	a_HI	B_HI	Xo_Ndem	b_Ndem	N_Root	N_Shoot	N_Prod	P_Root	Max_RD	T_MaxRD	T_Sen	T_Mat	Xo_Cover	b_Cover	a_cover
Barley (Spring)	Lit	Lit	Lit	Lit	Whe	Whe	Lit	Lit	Lit	Lit	Lit	Lit	Whe	Whe	Whe	Whe	Whe
Maize (Short)	Sim	Sim	Sim	Sim	Sim	Sim	Lit	Lit	Lit	Lit	Lit	Lit	Sim	Sim	Sim	Sim	Sim
Maize (Med)	Sim	Sim	Sim	Sim	Sim	Sim	Lit	Lit	Lit	Lit	Lit	Lit	Sim	Sim	Sim	Sim	Sim
Maize (Long)	Sim	Sim	Sim	Sim	Sim	Sim	Lit	Lit	Lit	Lit	Lit	Lit	Sim	Sim	Sim	Sim	Sim
Oats (Spring)	Lit	Lit	Lit	Lit	Whe	Whe	Lit	Lit	Lit	Lit	Lit	Lit	Whe	Whe	Whe	Whe	Whe
Oats (Autumn)	Lit	Lit	Lit	Lit	Whe	Whe	Lit	Lit	Lit	Lit	Lit	Lit	Whe	Whe	Whe	Whe	Whe
Wheat (Spring)	Sim	Sim	Sim	Sim	Sim	Sim	Lit	Lit	Lit	Lit	Lit	Lit	Sim	Sim	Sim	Sim	Sim
Wheat (Autumn)	Sim	Sim	Sim	Sim	Sim	Sim	Lit	Lit	Lit	Lit	Lit	Lit	Sim	Sim	Sim	Sim	Sim
Green manure																	
Brassica	Lit	Lit	Lit	Lit	Bro	Bro	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Bro	Bro	Lit
Mustard	Lit	Lit	Lit	Lit	Bro	Bro	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Bro	Bro	Lit
Lupins	Lit	Lit	Lit	Lit	Pea	Pea	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Pea	Pea	Lit
Phacelia	Lit	Lit	Lit	Lit	Pea	Pea	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Pea	Pea	Lit
Seed crops																	
Clover (1st year)	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit
Ryegrass (1st year)	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit
Vegetables: greens																	
Broccoli (winter/spring)	Sim	Sim	Sim	Sim	Sim	Sim	Lit	Lit	Lit	Lit	Lit	Lit	Sim	Sim	Sim	Sim	Sim
Broccoli (summer)	Sim	Sim	Sim	Sim	Sim	Sim	Lit	Lit	Lit	Lit	Lit	Lit	Sim	Sim	Sim	Sim	Sim
Brussel Sprouts	Lit	Lit	Lit	Lit	Bro	Bro	Lit	Lit	Lit	Lit	Lit	Lit	Bro	Bro	Bro	Bro	Lit
Cabbage(winter/spring)	Lit	Lit	Lit	Lit	Bro	Bro	Lit	Lit	Lit	Lit	Lit	Lit	Bro	Bro	Bro	Bro	Lit
Cabbage(summer)	Lit	Lit	Lit	Lit	Bro	Bro	Lit	Lit	Lit	Lit	Lit	Lit	Bro	Bro	Bro	Bro	Lit
Cauliflower(winter/spring)	Lit	Lit	Lit	Lit	Bro	Bro	Lit	Lit	Lit	Lit	Lit	Lit	Bro	Bro	Bro	Bro	Lit
Cauliflower(summer)	Lit	Lit	Lit	Lit	Bro	Bro	Lit	Lit	Lit	Lit	Lit	Lit	Bro	Bro	Bro	Bro	Lit

Parameter	Typical Yield	k_DM	a_HI	B_HI	Xo_Ndem	b_Ndem	N_Root	N_Shoot	N_Prod	P_Root	Max_RD	T_MaxRD	T_Sen	T_Mat	Xo_Cover	b_Cover	a_cover
Lettuce	Sim	Sim	Sim	Sim	Sim	Sim	Lit	Lit	Lit	Lit	Lit	Lit	Sim	Sim	Sim	Sim	Sim
Spinach	Lit	Lit	Lit	Lit	Let	Let	Lit	Lit	Lit	Lit	Lit	Lit	Let	Let	Let	Let	Lit
Vegetables: legumes																	
Green Beans	Lit	Lit	Lit	Lit	Pea	Pea	Lit	Lit	Lit	Lit	Lit	Lit	Pea	Pea	Pea	Pea	Lit
Dried Beans	Lit	Lit	Lit	Lit	Pea	Pea	Lit	Lit	Lit	Lit	Lit	Lit	Pea	Pea	Pea	Pea	Lit
Lentils	Lit	Lit	Lit	Lit	Pea	Pea	Lit	Lit	Lit	Lit	Lit	Lit	Pea	Pea	Pea	Pea	Lit
Green Peas	Lit	Lit	Lit	Lit	Pea	Pea	Lit	Lit	Lit	Lit	Lit	Lit	Pea	Pea	Pea	Pea	Lit
Pea	Sim	Sim	Sim	Sim	Sim	Sim	Lit	Lit	Lit	Lit	Lit	Lit	Sim	Sim	Sim	Sim	Sim
Vegetables:root																	
Kumara	Lit	Lit	Lit	Lit	Pot	Pot	Lit	Lit	Lit	Lit	Lit	Lit	Pot	Pot	Pot	Pot	Lit
Potatoes (Short)	Sim	Sim	Sim	Sim	Sim	Sim	Lit	Lit	Lit	Lit	Lit	Lit	Sim	Sim	Sim	Sim	Sim
Potatoes (Medium)	Sim	Sim	Sim	Sim	Sim	Sim	Lit	Lit	Lit	Lit	Lit	Lit	Sim	Sim	Sim	Sim	Sim
Potatoes (Long)	Sim	Sim	Sim	Sim	Sim	Sim	Lit	Lit	Lit	Lit	Lit	Lit	Sim	Sim	Sim	Sim	Sim
Beets	Lit	Lit	Lit	Lit	Pot	Pot	Lit	Lit	Lit	Lit	Lit	Lit	Pot	Pot	Pot	Pot	Lit
Carrots	Lit	Lit	Lit	Lit	Pot	Pot	Lit	Lit	Lit	Lit	Lit	Lit	Pot	Pot	Pot	Pot	Lit
Parsnips	Lit	Lit	Lit	Lit	Pot	Pot	Lit	Lit	Lit	Lit	Lit	Lit	Pot	Pot	Pot	Pot	Lit
Vegetables:other																	
Sweetcorn	Lit	Lit	Lit	Lit	Mai	Mai	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Mai	Mai	Mai
Squash	Sim	Sim	Sim	Sim	Sim	Sim	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Sim	Sim	Sim
Onions	Sim	Sim	Sim	Sim	Sim	Sim	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Sim	Sim	Sim
Tomato	Lit	Lit	Lit	Lit	Pot	Pot	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Pot	Pot	Lit
Oats & Rye	Lit	Lit	Lit	Lit	Whe	Whe	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Lit	Whe	Whe	Lit

Sim = derived from simulation analysis

Lit = derived from the literature or expert comment in the absence of literature

Whe = assumed to be the same as wheat
Pot = assumed to be the same as potato
Mai = assumed to be the same as maize
Bro = assumed to be the same as broccoli
Let = assumed to be the same as lettuce
Ch = Chakwizira *et al*. (2011)

4. Crop growth properties

This section covers the growth characteristics of a crop that is sown and then harvested at maturity or when the crop ends. This section does not cover permanent pasture, annual ryegrass, or regrowth seed crops which are modelled separately. Growth characteristics of a crop that can be harvested and regrown are described in section 7.

4.1. Growth curve

For crops, the proportion of total yield that was achieved in a given month is based on the accumulated thermal time (section 4.1.3). The initial growth of seed crops uses the same method until the first harvest of seed occurs. After harvest, seed crops become regrowth crops and follow a growth pattern similar to pasture.

The relationship between potential yield and thermal time for was used to derive the biomass coefficients X_o_Biomass and b_biomass (Brown, 2009). Individual crop values are shown in Table 5. Examples of growth curves for Turnips and Kale are shown in Figure 1 (as published by Chakwizira *et al*., 2011). Growth curves for crops that regrow after being defoliated were also developed (section 7).

As final crop yield is entered by the user, the growth curve is used to estimate monthly N uptakes (section 5.3).

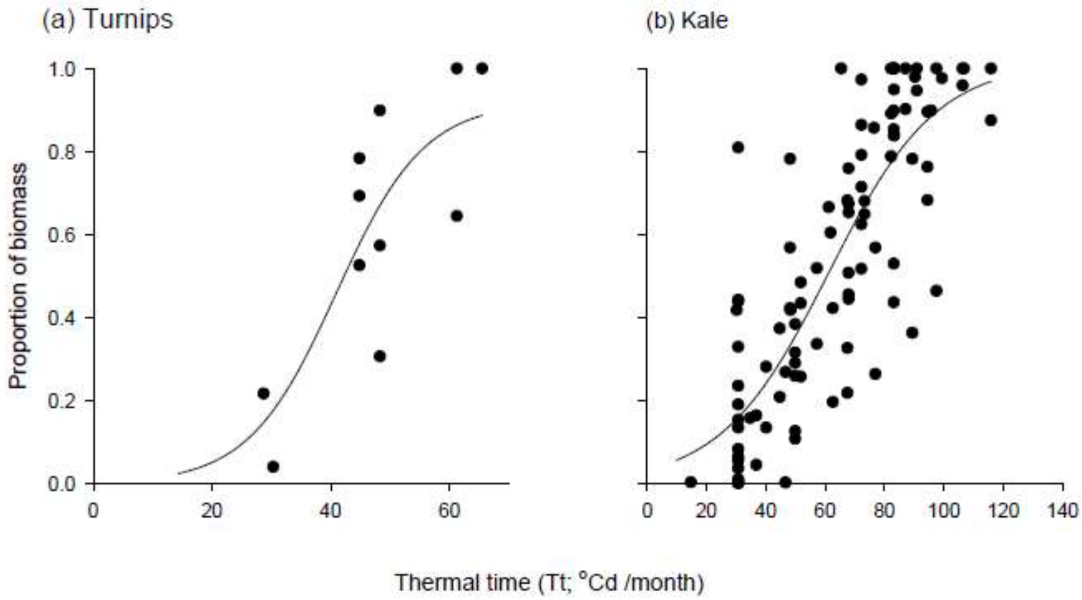

Figure 1. Proportion of biomass in relation to accumulated thermal time for (a) turnips and (b) kale (taken from Chakwizira *et al*., 2011).

4.1.1. Standard crop growth curve

The proportion of final biomass that has accumulated up until a given month is estimated using a sigmoidal relationship as:

Equation 1: $pBiomass_{mon} = 1 / (1 + Exp(-((ThermalTime_{mon} - X_o\_Biomass) / b\_biomass)))$

ThermalTime is the thermal time (°C month) [section 4.1.3].

X_o_Biomass is the thermal time taken for the crop to grow to half of its final biomass (°C months) [Table 5, section 3.1.2].

b_biomass is the curvature parameter [Table 5, section 3.1.2].

To prevent small estimates of monthly N uptake when a crop is close to its potential yield, a limit has been set. If pBiomass is greater than 0.95, then it is set to 1.

4.1.2. Adjustments

The user can specify the month when the crop stops growing. Cultivation of grain and vegetable crops induces a harvest event. For fodder and forage crops, the user can specify that the crop is harvested before sufficient thermal time has elapsed, that is, the final harvest is occurring before pBiomass is 1. As yield is supplied by the user, the growth curve is adjusted so that pBiomass is 1 at harvest, that is:

Equation 2: $pBiomass_{mon} = pBiomass_{mon} / pBiomass_{finalmon}$

$pBiomass_{finalmon}$ is the estimated value when final harvest occurs.

4.1.3. Thermal time

Thermal time is used to model crop growth. Typically this is calculated as the cumulative sum of daily average temperature to give °C days. For the purpose of this monthly model, thermal time is based on monthly mean air temperature (Climate chapter).

For the month of sowing, monthly thermal time (ThermalTime, °C month) is the mean monthly air temperature. Thereafter, monthly thermal time is increased each month by adding the mean monthly temperature until the crop is finished.

The thermal time (°C month) when leaf area senescence begins and when the crop is mature is shown in section 3.1.2 and used in the section 4.4.

4.2. Harvest Index

Normally, harvest index (HI) refers to the harvestable yield of a crop (usually the reproductive sink, i.e. the seed, grain or fruit fraction) as a proportion of the total yield. For crops used to feed animals, the HI is assumed to be equivalent to the proportion of the crop utilised as animal feed.

4.2.1. Harvest index coefficients

For grain crops, the harvest index was determined by dividing grain yield by total biomass production and then harvest index was plotted back against grain yield for each simulation. The parameters from the fitted regression enable harvest index to be related to the grain yield that the user specifies and so give a more accurate estimation of residue returns than using a constant harvest index. (Brown, 2009). For other crops the harvest index was assumed to not change with yield.

A similar approach was used for fodder crops whereby fitted regression coefficients (a_harvest and b_harvest) were determined from the relationship between crop yield and the proportion of the crop utilised (Chakwizira *et al*., 2011). This relationship had a negative slope because higher yielding crops are more likely to have greater trampling losses and/or residuals (Chakwizira *et al*., 2011) and for some crops such as kale, the proportion of unutilised stems increased at higher yields. The relationship between yield and harvest index (proportion of above ground growth utilised by animals) for two fodder crops are shown in Figure 2.

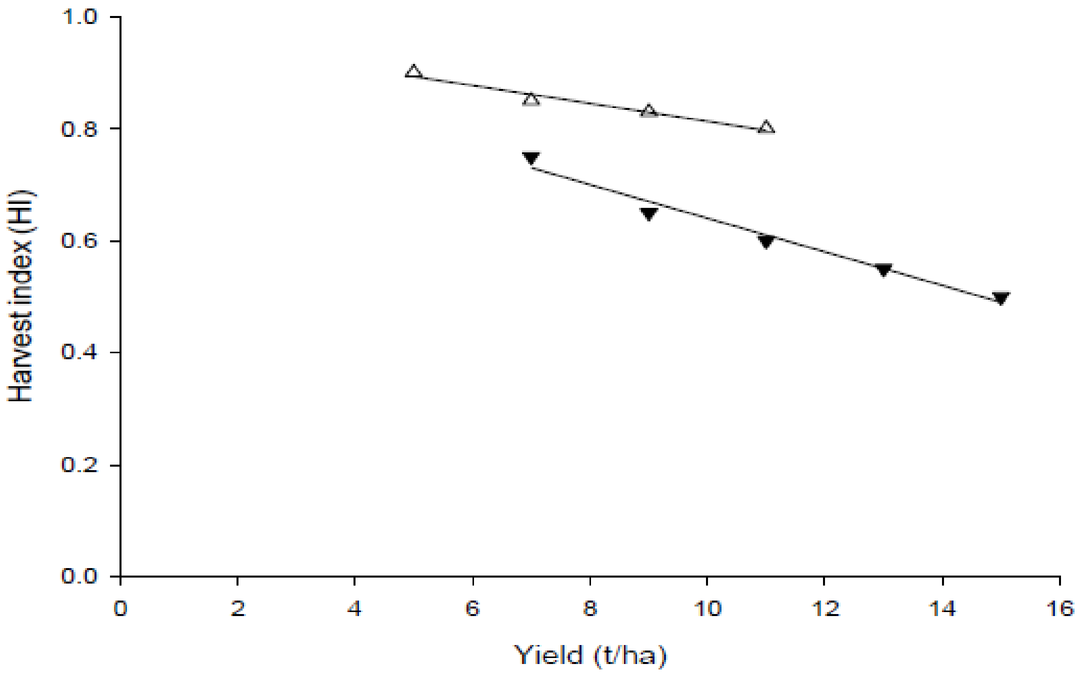

Figure 2. Harvest index in relation to total dry matter yield for kale (▼) and turnips (Δ) (From Chakwizira *et al*., 2011).

4.2.2. Estimating harvest index

Harvest index is estimated as:

Equation 3: HarIndex = a_Harvest + b_Harvest * Yield

a_Harvest and b_Harvest are regression coefficients [Table 5, section 3.1.2].

Yield is the DM yield (kg DM/ha) [section 4.3.1].

For broccoli, the harvest index was doubled if the Chinese cut method was used for harvest.

4.3. Crop yield

The user either enters the product (crop) yield, or if not entered, then the typical crop yield (section 3.1.1, Table 4) is used. These are on a T/ha of product basis.

The following component yields (kg DM/ha) are estimated for crops:

- Product yield (M_product) is the harvested yield removed as product, such as grains or vegetables at harvest.
- Top yield (M_tops) is the amount of defoliated vegetative material removed.
- Residue yield (M_Residue) is the amount of above ground material not harvested, defoliated, or if grazed, unutilised.
- Root yield (M_root) is the amount of material in roots at harvest.

In addition, wet weight (Wetweight), which is is the wet weight of crop removed, is estimated and used for greenhouse gas emission calculations.

4.3.1. Crop yield and wet weight

The entered product (crop) yield or default yield is on a T/ha of product basis. Hence it is the fresh weight of product that is used. The yield of grain crops entered as dry grain, which still contains some moisture. The exception is fodder crop and forages, the yield of which is entered on a DM basis. Hence crop yield (kg DM/ha), and the wet weight of the crop (kg WW/ha) is estimated as:

Equation 4: Yield = YieldT * 1000

Equation 5: $\text{Wetweight} = \text{YieldT} * 1000 / \text{DMcontent}_{\text{crop}}$

YieldT is the entered or default crop yield (T/ha).

DMcontent in the DM content of the product (kg/kg) [Table 5, section 3.1.2].

1000 converts T to kg.

For crops other than fodder crop and forages, the entered yield is the yield of the product, and hence is a wet weight. Thus crop yield and wet weight is estimated as:

Equation 6: Yield = YieldT * 1000 * DMcontent

Equation 7: Wetweight = YieldT * 1000

Some growers leave a higher proportion of stem which is referred to as the ‘Chinese cut’. A survey of 25 heads of broccoli cut using the standard commercial cut and Chinese cut methods, indicated that yield of broccoli removed using Chinese cut method was 2.3 times that using the conventional cut, at about 74% of total above ground plant yield. A conservative approach was taken and yield and Wetweight are doubled if the Chinese cut is used.

4.3.2. Product, top and residue yields

Product, top and residue yields are estimated from above ground yield, which is estimated as:

Equation 8: AbovegrdYield = Yield / HarIndex

Yield is the crop yield (kg DM/ha) [section 4.3.1].

HarIndex is the harvest index [section 4.2].

For forages, the top yield is the crop yield, and product yield is zero. Otherwise the top yield is zero and product yield is the crop yield. The vegetative yield of seed crops is handled separately (unpublished).

Residue yield is the difference between above ground yield and crop yield, that is:

Equation 9: M_Residue = AbovegrdYield - Yield

4.3.2.1. *Green manures*

For green manures, it is assumed that all the crop is returned to the soil. The yield of the crop is not entered as it is assumed that the yield of a green manure crop, which is not harvested but returned to the soil, is unlikely to be known by the user. Hence yield of product and tops is assumed to be zero, the yield of residues (kg DM/ha/crop) is estimated as:

Equation 10: M_Residue = DefaultYield * 1000

DefaultYield is the crop default yield (T DM/ha) [section 3.1.1, Table 4].

4.3.3. Root yields

The yield of roots (kg DM/ha/crop) is estimated as:

Equation 11: M_Roots = (M_Tops + M_Product + M_Residue) * p_root_{crop}

M_Tops, M_Product, M_Residue are above ground component yields (kg DM/ha) [section 4.3.2].

p_root is the root yield as a proportion of above ground yield [section 3.1.1, Table 4].

4.4. Crop cover

Cover is the proportion of the land area that is covered by a crop canopy. The time to full canopy closure also affects the total amount of radiation accumulated by the crop and therefore the total DM produced by the crop. Radiation capture is more efficient with earlier closure of the crop canopy. This is captured using the biomass relationship (section 4.1).

Crop transpiration is used to estimate the crop water balance, soil drainage and, therefore, N leaching (Hydrology chapter). The rate of transpiration is determined by crop cover. Initially, and in many crops, a sigmoidal response between cover and thermal time is observed (Figure 3).

In crops such as wheat, there is a loss of cover due to vegetation senescing as grain fill occurs. The point that senescence occurs is determined by thermal time (T_Sensescence). An example is shown in Figure 4 for wheat.

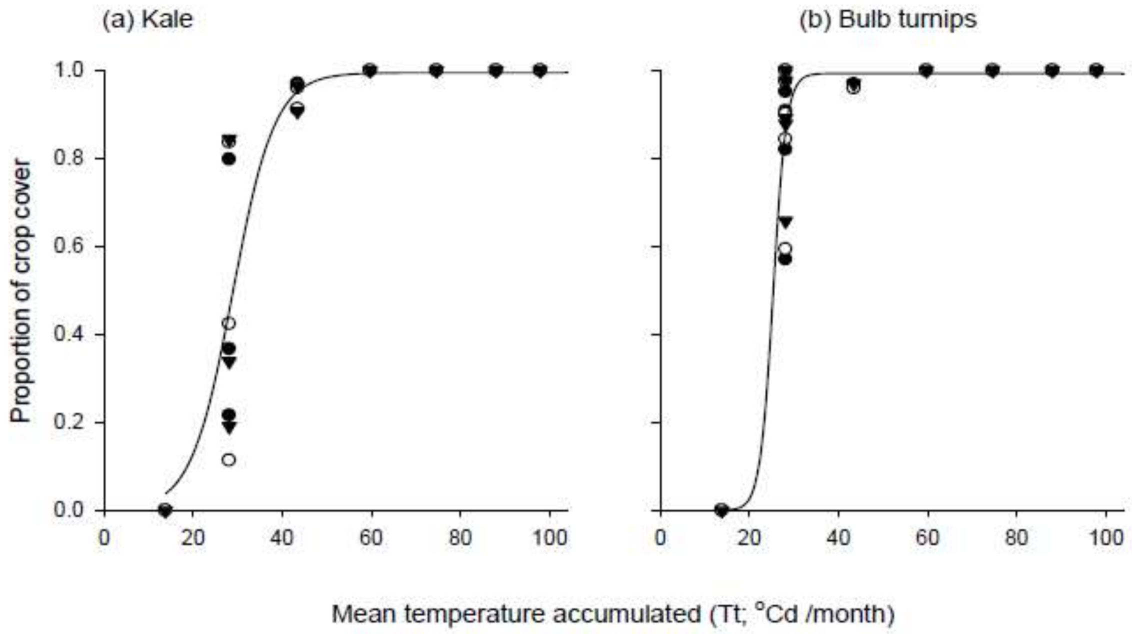

Figure 3. Crop cover in relation to accumulated thermal time for (a) kale and (b) turnips (From Chakwizira *et al*., 2011).

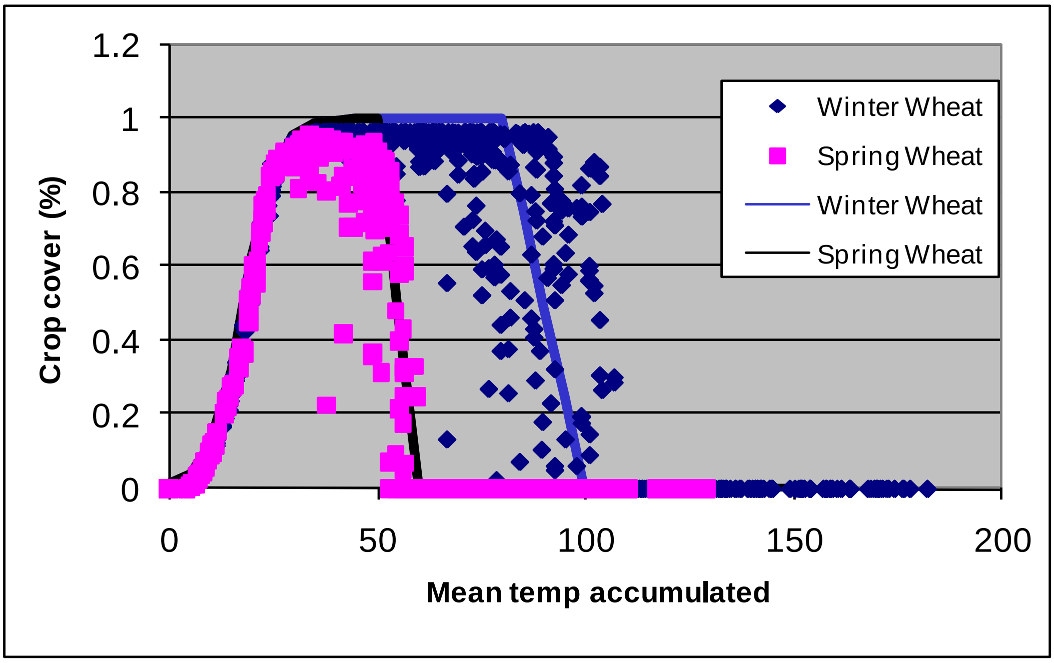

Figure 4. Crop cover in relation to accumulated thermal time for spring and winter wheats (from Brown 2009).

4.4.1. Crop cover coefficients

Crop cover coefficients (X_o_cover and b_cover) were calculated from the relationship between crop cover and accumulated thermal time (calculated from monthly average air temperature). Crop cover is estimated from specific crop cover coefficients and thermal time. The pattern of crop cover was quantified in relation to thermal time (averaged per month; °C month) using a sigmoid function.

A sigmoidal function was fitted to these relationships to determine the values of X_o_cover and b_cover (Figure 2). The crop cover coefficients define how quickly crop leaf area develops relative to ground area. The function had two further parameters (T_Senescence and T_maturity) which describes when leaf area senescence begins (and cover declines) and when the crop reaches maturity or has no ground cover because it has been harvested.

4.4.2. Estimating cover

For a given month, if the monthly thermal time is less than the thermal time to senescence, then cover is estimated as:

Equation 12: $cover_{mon} = a\_cover / (1 + Exp(-(ThermalTime_{mon} - X_o\_Cover) / b\_Cover))$

ThermalTime is the thermal time (°C month) [section 4.1.3].

a_cover is the maximum cover [section 3.1.2, Table 5].

X_o_cover is the thermal time taken to reach half the final biomass (°C months) [section 3.1.2, Table 5].

b_cover is the curvature parameter [section 3.1.2, Table 5].

else if the monthly thermal time is less than the thermal time to maturity, cover declines linearly with thermal time:

Equation 13: $cover_{mon} = a\_cover * ((ThermalTime_{mon} - T\_Senescence) / (T\_Maturity - T\_Senescence))$

ThermalTime is the thermal time (°C month) [section 4.1.3].

T_Maturity is the thermal time that the crop takes to reach maturity (°C month) [section 3.1.2, Table 5].

T_Senescence is the thermal time at which the crop starts to senesce (°C month) [section 3.1.2, Table 5].

Otherwise cover is zero.

4.5. Crop rooting depth

The crop rooting depth is used to estimate the amount of plant available water (PAW) available for transpiration (Hydrology chapter). In a given month, the depth of roots (Zroots, m) is initially estimated as:

Equation 14: $Zroots_{mon} = Max\_RDepth * ThermalTime_{mon} / TmaxRD$

Max_RDepth is the maximum rooting depth of a given crop (m) [Table 5, section 3.1.2].

ThermalTime is the thermal time (°C month) [section 4.1.3].

TmaxRD is the thermal time (°C month) for roots to reach maximum depth.

Assuming that crop roots grow at the rate of 0.015 m/°C month, the thermal time to reach maximum rooting depth is estimated as:

Equation 15: TmaxRD = Max_RDepth] / 0.015

Max_RDepth is the maximum rooting depth of a given crop (m) [Table 5, section 3.1.2].

The depth reached by the crop's roots in a given month is then the lesser of Zroots or Max_RDepth (Table 5, section 3.1.2), and if entered the depth to the impeded layer or the depth to the maximum profile rooting depth.

5. Crop nutrient uptake

At maturity, crops consist of product removed, residues, and roots. These components have different nutrient compositions. It is assumed that total nutrient uptake is the sum of the demand (i.e. yield and nutrient content) of each component.

5.1. Nutrient concentrations

The concentration of nutrients in product (prodconc) and residues (resconc) of each crop is shown in Table 6 and Table 7 respectively. Root concentrations are estimated as described in section 5.1.1. There was insufficient data to indicate how nutrient content varied with factors such as soil test values or fertiliser inputs. Thus a constant value is used.

The nutrient content associated with acidity is calculated as the excess cations, which is estimated using the nutrient contents of the other nutrients.

5.1.1. Root concentrations

For N, root concentrations (%) are taken from Table 6, section 3.1.3.

Root concentrations for nutrients other than N are based on the product concentration. If top yield is greater than zero, or the residue concentration is on a DM basis, product concentrations are then multiplied by a factor to convert them to root concentrations. This factor (Table 10) was based on root and shoot concentrations measured in hydroponic solutions (Wheeler, 2016) after 4 weeks growth.

Table 10. Factor for converting top nutrient concentration to root nutrient concentrations.

Type	P	K	S	Ca	Mg	Na
Cereals	0.9	0.9	0.8	0.33	0.9	1.2
Legumes	1.0	1.0	0.8	0.2	0.5	1.2
Root	0.8	1.0	1.0	0.4	0.9	1.2
Seed	0.9	0.9	0.8	0.33	0.9	1.2
Other	0.8	1.0	1.0	0.4	0.9	1.2

5.1.2. Dry or fresh concentrations

All concentrations shown in Table 6 and Table 7 are on a percentage basis. However, some concentrations in Table 6 (product concentrations) are on a fresh weight basis, whereas others are on a dry weight basis.

The factor to convert concentrations to proportion on a DM basis when data is on a dry weight basis is:

Equation 16: dryfresh = 1 / 100

whereas if data is fresh weight then the conversion is estimated as:

Equation 17: dryfresh = (1 / DMcontent) * 1/100

DMcontent in the DM content of the product (kg/kg) [Table 5, section 3.1.2].

All nitrogen concentrations are on a DM basis.

5.2. Nutrient demands

Demand for tops, product and roots (kg nutrient/ha) is estimated as:

Equation 18: $Demand\_Product_{nut} = M\_Product * prodconc_{nut} * dryfresh$

Equation 19: $Demand\_Tops_{nut} = M\_Top * prodconc_{nut} * dryfresh$

Equation 20: $Demand\_Roots_{nut} = Rootyld * rootconc_{nut}$

M_Product, M_Tops and M_Roots are yields of product, tops and roots (kg DM/ha) [section 4.3].

prodconc and rootconc is the concentration of product and roots respectively (%) [Table 6, section 3.1.3 and section 5.1.1 respectively].

Dryfresh is the conversion from % in the database to kg nutrient/kg DM [section 5.1.2].

For green manures, residue demand is estimated as:

Equation 21: $Demand\_Residue_{nut} = M\_Residue * prodconc_{nut}$

otherwise it is estimated as:

Equation 22: $Demand\_Residue_{nut} = M\_Residue * resconc_{nut}$

Total demand (uptake) is then the sum of demand from products, tops, residues, and roots.

5.3. Monthly N demand

Monthly N demand, or uptake, is used in the crop nitrogen model (Crop N model chapter). Monthly N uptake is only required for N. Monthly N uptake was calculated as:

Equation 23: $Uptake_{N, mon} = TotalNUptake * (p\_NDemand_{mon} – p\_NDemand_{mon-1})$

TotalNUptake is total crop N demand (kg N/ha) [section 5.2].

p_NDemand is the proportion of total N taken up in a given month [section 5.4].

5.4. N uptake curve

Analysis of wheat data showed that there was good correlation between shoot biomass and shoot N uptake. Hence it is assumed that the pattern of N uptake is similar to that of biomass accumulation. Thus, the proportion of total N taken up in a given month (pNdemand) is the same as proportion of biomass accumulated in a given month (p_Biomass). This assumption is applied to all crops.

The user can also select the month the crop stops taking up N. The model allows a 2 month extension of uptake beyond that predicted by the growth curves, or for uptake to stop before that predicted by the growth curves. In these cases, the N uptake curve needs to be adjusted. If the monthly N uptake is stopped is after pBiomass has reached 1 (i.e. uptake lasts longer than that estimated by the growth curve), then in the month uptake is stopped, the proportion of total N taken up in a given month is set to 1.

5.4.1. Extending the uptake period

If the difference between the month pBiomass is 1 and the month uptake ends is one month (extend uptake by 1 month), then in the month of sowing:

Equation 24: $p\_NDemand_{mon} = pBiomass_{mon} / 2$

Otherwise for months other than the month of sowing or the month uptake ends, then:

Equation 25: $p\_NDemand_{mon} = (p\_NDemand_{mon} + p\_NDemand_{mon - 1}) / 2$

If the difference between the month pBiomass is 1 and the month uptake ends is two months (extend uptake by 2 months), then in the month of sowing:

Equation 26: $p\_NDemand_{mon} = pBiomass_{mon} / 3$

In the month after sowing:

Equation 27: $p\_NDemand_{mon} = (pBiomass_{mon} + pBiomass_{mon-1}]) / 3$

In the month before the end uptake ends:

Equation 28: $p\_NDemand_{mon} = (pBiomass_{mon-1} + pBiomass_{mon-2}]) / 2$

Otherwise for other months:

Equation 29: $p\_NDemand_{mon} = (pBiomass_{mon} + pBiomass_{mon-1} + pBiomass_{mon-2}]) / 3$

5.4.2. Reducing the uptake period

If the month uptake stops is before maximum growth is achieved (pBiomass < 1) then:

Equation 30: $pNDemand_{mon} = pBiomass_{mon} / pBiomass_{finalmon}$

pBiomassfinalmon is the estimated value when final harvest occurs.

6. N fixation

For leguminous crops (beans, lentils, peas, seed clover), the total amount of N fixed is based on a default value estimated from literature and expert opinion. The monthly amount of N fixed is estimated as:

Equation 31: $BaseNfixed_{mon}$ = crop_Nfixation * ($pNDemand_{mon}$ – $pNDemand_{mon-1}$)

Crop_Nfixation is the amount of N fixed per crop (kg N/ha) [Table 11].

pNDemand is the the proportion of total N taken up in a given month [section 5.3].

For clover seed crops, the model assumes that 80% of the N uptake is from N fixation.

The base amount of N fixed is reduced for inorganic N added to the block, with the reduction (kg N/ha/month) estimated as:

Equation 32: fert_reduct = 0.2 * (SolubleFertN + N_irrig)

fertNin is the amount of soluble N fertiliser applied in a given month (kg N/ha/month [Crop N model chapter].

irrNin is the amount of N fertiliser applied in a given month (kg N/ha/month [Crop N model chapter].

Table 11. Nitrogen (N) fixed for crops that can fix nitrogen (legumes).

Crop	N fixed (kg N/ha)
Beans (green)	10
Beans (dried)	10
Lentils	30
Peas (green)	10
Peas (dried)	10
Lupins	24

7. Defoliated crops

Autumn sown oats and wheat can be defoliated (grazed or cut and carry) in early spring, and then growth continues to produce grain. Forages, excluding maize for silage, also regrow after defoliation. This section covers the modelling of regrowth after defoliation. **Seedling growth** refers to growth from sowing to maturity, and growth, cover and uptake characteristics are estimated using the standard crop methods (section 4).

The regrowth of pasture, annual ryegrass and regrowth seed crops are handled separately.

7.1. Component yields

The duration of a defoliated crop (time to maturity) will be similar to that of a non-defoliated crop because the timing of flower and subsequent development is controlled by photological events that are independent of defoliation. For each subsequent regrowth the total biomass produced (and N uptake in tops) will decrease and the duration of the regrowth will be compressed so the defoliated crop matures on a similar date as a non-defoliated crop.

For a given crop, the yield of the crop at the final harvest is entered. This yield is assumed to include any reduction in yield, given that defoliation(s) can cause a reduction in product yield. Note that some crops will not have their yield reduced by defoliation because their harvest index will increase. This is captured within the current mechanism.

As the entered yield is for the defoliated crop, the yields for the seedling growth curve is increased as:

Equation 33: M_Residue = M_Residue * CropYldAdj

Equation 34: M_Product = M_Product * CropYldAdj

Equation 35: M_Tops = M_Tops * CropYldAdj

M_residue, M_product and M_tops is the yield for the seedling crop (kg DM/ha) [section 4.3].

CropYldAdj is the adjustment factor [Equation 36].

The adjustment factor is estimated as:

Equation 36: CropYldAdj = (2 - MaxParamAdj) / (2 - ParamAdj)

ParamAdj is the adjustment factor for seedling parameters [section 7.6].

MaxParamAdj is the maximum value of ParamAdj for the crop.

7.2. Growth curves

For crops where regrowth occurs after defoliation, the proportion of biomass in a given month can be calculated from those specified for the seedling crops. The growth curve up to the first defoliation is estimated as for a seedling crop (section 4.1.1). In the month of defoliation and following months, the growth curve is estimated as:

Equation 37: $pBiomass_{mon} = 1 / (1 + Exp(-((DefolThermalTime_{mon} - X_o\_Biomass * 0.75 * ParamAdj_{mon}) / (b\_biomass * ParamAdj_{mon}))))$

DefolThermalTime is the thermal time after defoliations (°C month) [section 7.5].

X_o_Biomass is the thermal time taken to reach half the final biomass (°C months) [Table 5, section 3.1.2].

b_biomass is the curvature parameter [Table 5, section 3.1.2].

ParamAdj is the adjustment factor for seedling parameters [section 7.6].

7.3. Cover

Following defoliation crops generally re-establish cover quite quickly. It is assumed that the loss of cover following senescence will follow a similar pattern to that of a seedling crop (section 4.4).

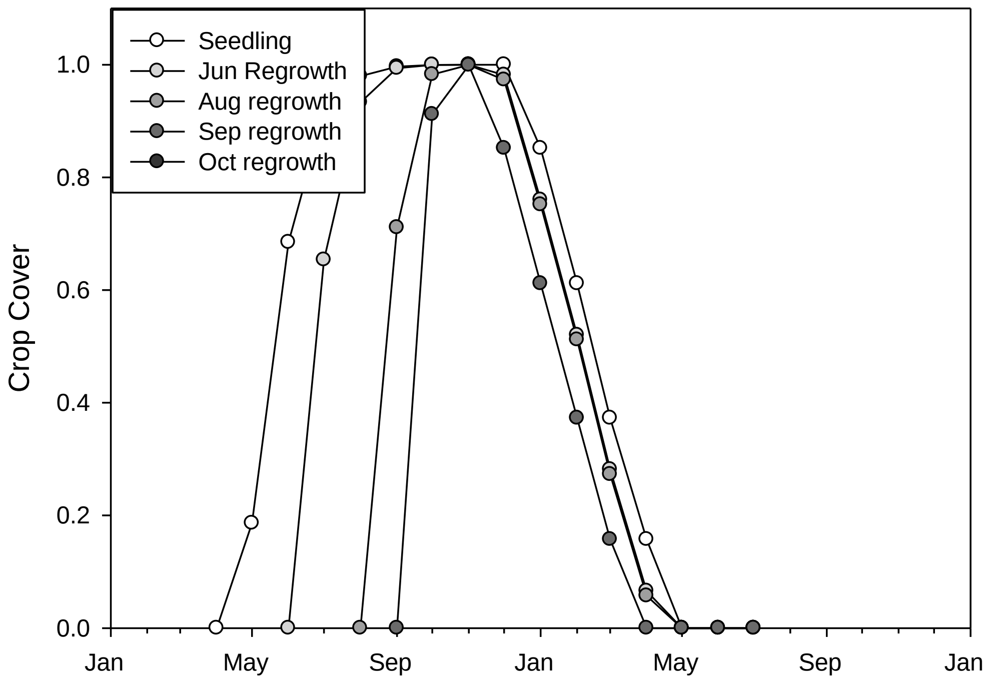

Figure 5. The typical relationship between crop cover and timing of defoliation in wheat (from Brown, 2009).

For a given month, if the thermal time since the last defoliation (defoliated thermal time) is less than the difference between thermal time to reach crop maturity and monthly thermal time, that is:

Equation 38: $DefolThermalTime_{mon} < T\_Maturity – ThermalTime_{mon}$

then

Equation 39: $cover_{mon} = a\_cover / (1 + Exp(-(DefolThermalTime_{mon} - Xo\_Cover * 0.25)) / b\_Cover))$

DefolThermalTime is the thermal time since the last defoliation (°C month) [section 7.5].

a_cover is the maximum cover [section 3.1.2, Table 5].

Xo_cover is the thermal time taken to reach half the final biomass (°C months) [section 3.1.2, Table 5].

b_cover is the curvature parameter [section 3.1.2, Table 5].

Else, if the defoliated thermal time is less than the difference between thermal time to reach senescence and monthly thermal time, that is:

Equation 40: $DefolThermalTime_{mon} < T\_Senescence – ThermalTime_{mon}$

then

Equation 41: $cover_{mon} = a\_cover - ((DefolThermalTime_{mon} - T\_Senescence +$

ThermalTime$_{mon}$) / (T_Maturity - T_Senescence))

DefolThermalTime is the thermal time since the last defoliation (°C month) [section 7.5].

a_cover is the maximum cover [section 3.1.2, Table 5].

ThermalTime is the thermal time since sowing (°C month) [section 4.1.3].

T_Maturity is the thermal time that the crop reaches maturity (°C month) [section 3.1.2, Table 5].

T_Senescence is the thermal time that the crop starts to senesce (°C month) [section 3.1.2, Table 5].

Otherwise cover is zero.

7.4. Monthly N demand

The monthly pattern of N uptake for a defoliated crop can then be calculated from the change in yield with defoliation (section 7.1) and the growth curves (section 7.2). An example of how the pattern of N uptake, and proportion of N uptake each month, would vary for different regrowth periods is shown in Figure 6 and Figure 7 respectively. The reduction in yield means that the potential N uptake for regrowth becomes progressively less as defoliations become later (towards final harvest).

For the example shown in Figure 6, if the user specifies one defoliation in September the crop N uptake would follow the solid black line for the seedling crop until September and then follow the line presented for the September defoliation. If additional defoliations are specified the N uptake would follow the 1st defoliation pattern until the date of the 2nd defoliation and then follow the pattern for the 2nd defoliation until harvest.

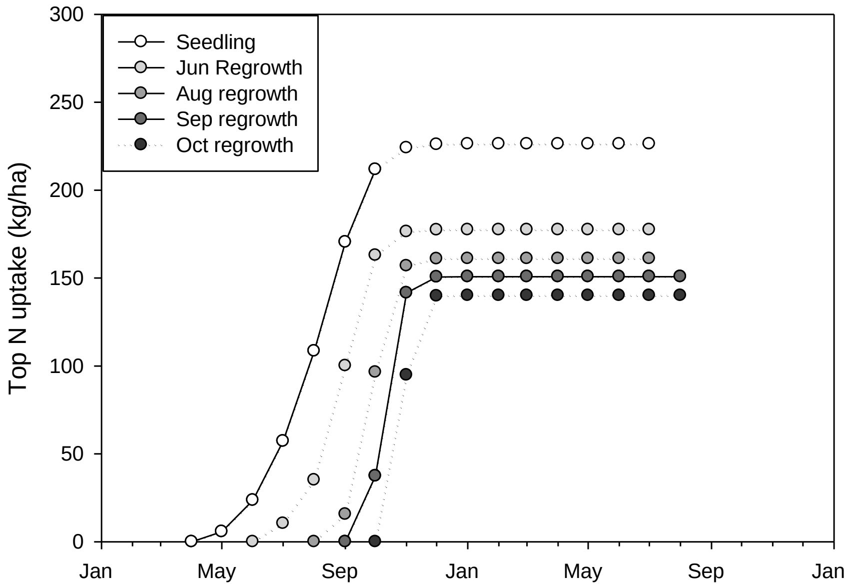

Figure 6. Uptake N by a crop after defoliation (from Brown, 2009).

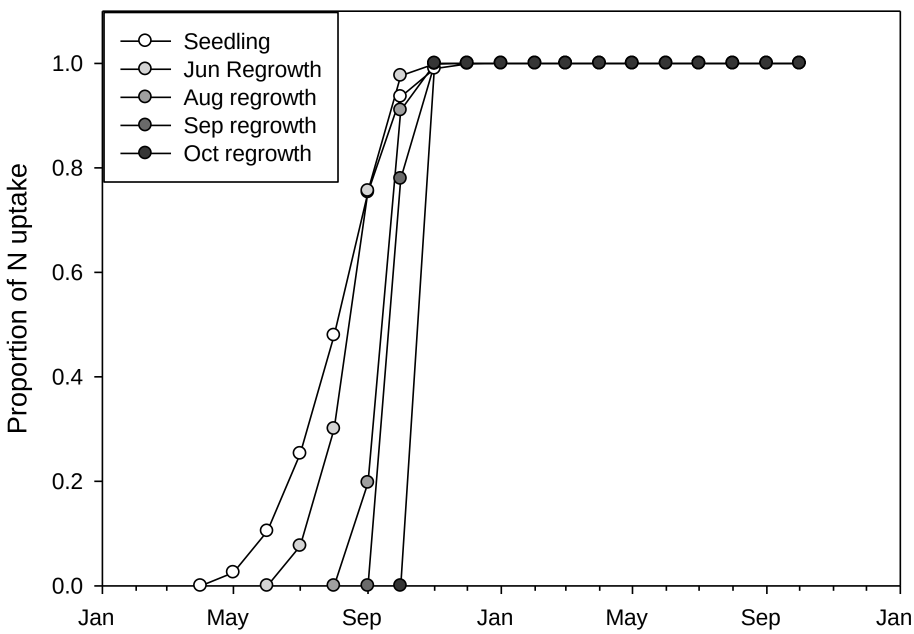

Figure 7. Proportion of N uptake for different times of defoliation (from Brown, 2009).

7.5. Defoliated thermal time

If the crop can be defoliated, then in the month of defoliation, the defoliated monthly thermal time (DefolThermalTime) is set to the mean monthly temperature (Climate chapter). Thereafter, defoliated monthly thermal time is increased each month by adding the mean monthly temperature until the crop is finished.

7.6. Parameter adjustment

Each month after defoliation, the proportion of biomass left is estimated as:

Equation 42: $ParamAdj_{mon} = (T\_Maturity * 0.7 - ThermalTime_{mon}) / (T\_Maturity * 0.7)$

T_Maturity is the thermal time for the crop to reach maturity (°C month) [section 3.1.2, Table 5].

ThermalTime is the thermal time since sowing for the month of defoliation (°C month) [section 4.1.3].

This function reduces in value the closer thermal time is to maturity time, such that after 70% of maturity, it is assumed that there is no additional regrowth.

8. References

Brown H 2009 Release documents from the SFF project Nitrogen Management for Environmental Accountability (unpublished).

Chakwizira E, de Ruiter J, Brown H, Wheeler D and Shepherd M 2011 Parameter development for adding fodder crops to OVERSEER® Nutrient Budgets: 1. kale and turnips In Adding to the knowledge base for the nutrient manager. (Eds L D Currie and C L Christensen), Fertilizer and Lime Research Centre, Occasional Report No. 24. http://flrc.massey.ac.nz/publications.html. Massey University, Palmerston North, February 2011 (12 pages).

Wheeler D M 2016 Relationship between shoot and root nutrient concentrations for a range of temperate pasture and cereal species. In: Integrated nutrient and water management for sustainable farming. (Eds L.D. Currie and R Singh), Fertilizer and Lime Research Centre, Occasional Report No. 29. http://flrc.massey.ac.nz/publications.html. Massey University, Palmerston North, New Zealand.

Wheeler D M, Sparling G P and Roberts A H C 2004 Trends in some soil test data over a 14 year period in New Zealand. New Zealand Journal of Agricultural Research 47: 155-166.