System Report: Grazed Orchards in England and Wales

Project name	AGFORWARD (613520)
Work-package	3: Agroforestry for High Value Tree Systems
Specific group	Grazed orchards in the England and Wales
Deliverable	Contribution to Deliverable 3.7 (3.1): Detailed system description of a case study system
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Authors	Paul J Burgess, Matthew Upson, Anil Graves and Silvestre Garcia de Jalon, Cranfield University, Cranfield, MK43 0AL, UK
Contact	p.burgess@cranfield.ac.uk
Approved	Anastasia Pantera (21 April 2016)

Contents

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1 Context

The AGFORWARD research project (January 2014-December 2017), funded by the European Commission, is promoting agroforestry practices in Europe that will advance sustainable rural development. The project has four objectives:

1. to understand the context and extent of agroforestry in Europe,
2. to identify, develop and field-test innovations (through participatory research) to improve the benefits and viability of agroforestry systems in Europe,
3. to evaluate innovative agroforestry designs and practices at a field-, farm- and landscape scale, and
4. to promote the wider adoption of appropriate agroforestry systems in Europe through policy development and dissemination.

This report contributes to Objective 2, Deliverable 3.7: "Detailed system description of case study agroforestry systems". The detailed system description includes the key inputs, flows, and outputs of the key ecosystem services of the studied system. It covers the agroecology of the site (climate, soil), the components (tree species, crop system, livestock, management system) and key ecosystem services (provisioning, regulating and cultural) and the associated economic values. The data included in this report will also inform the modelling activities which help to address Objective 3.

2 Background

The initial stakeholder report (Burgess, 2014) and the research and development protocol (Upson et al. 2015) provide background data on grazed orchards in England and Wales. In England, the grazing of orchards has long been a common practice (Hoare, 1928) and it is still practised on a considerable proportion of traditional orchards (Burrough et al. 2010). However the practice is relatively uncommon on commercial cider 'bush' orchards, which are now the main type of orchard used for cider apple production in the UK. The production of blemish free apples generally requires an intensive agrochemical programme (Pennell, 2006).

Commercial bush orchards can be mown eight times per year, an activity involving labour and machinery costs. The introduction of sheep to the orchard can minimise the need for such mowing and at the same time it can positively contribute to providing animal feed for sheep production enterprises. However the livestock can also incur costs, and bring additional complexity and administrative burdens to bush orchard cider production (Burgess, 2014; Corroyer, 2014; Durrant and Durrant, 2009). One other potential synergy is the better control of apple scab (*Venturia inaequalis*), since sheep can eat apple leaves as they fall to the ground, and help to decompose old leaves by trampling, thus reducing the refuge for the fungus (Corroyer, 2014; McAdam, 2014).

3 Update on field measurements

Field measurements described in the research and development protocol (Upson et al., 2015) began in early June 2015, and continue to be conducted by the farmer. A meeting at the trial site occurred on 16 December 2015.

4 Description of system

Table 1 provides a general description of the grazed orchard agroforestry system. A description of a specific case study system is provided in Table 2.

Table 1. General description of grazed orchard systems in England and Wales

General description of system	
Name of group	Grazed orchards in England and Wales
Contact	Paul Burgess
Work-package	3: High value trees
Associated WP	Use of livestock
Geographical extent	Grazed cider orchards are found in England, Wales, Northern Ireland and northern France.
Estimated area	The total area of apple orchards in 2012 in England and Wales is recorded as 14,470 ha, with 7,180 ha identified as cider orchards (DEFRA, 2013). Including pears, plums, and cherries the total orchard area is 17,620 ha.
Typical soil types	Cambisols
Description	Cider apple orchards are planted to produce apples which can be used to produce cider. This can occur in traditional or "bush" orchards. Because the initial product is apple juice, the appearance of the apple is less important than if the apples are being sold as dessert apples. The process of fermenting the apples, should also minimise the risk of faecal contamination. To ease of the harvest of the apples, the grass is usually mown during the year. Grazing provides a means of maintaining a short sward and providing fodder for sheep. The sheep may be lambs which are being fattened or ewes that need to maintain body weight until the next lambing season.
Tree species	Apple (*Malus domestica*)
Tree products	Apples for production of apple juice which is then used to make an alcoholic beverage called "cider". Vylupek (2010) quotes a mean apple yield from UK orchards of 15.7 t ha^{-1}. Centre for Alternative Land Use (2007) quotes a yield of 12 t ha^{-1} on a poor site to 20 t ha^{-1} on a poor site. Fairs (2010), quoted by Vylupek (2010) quotes a mature (10 years) yield of about 50 t ha^{-1}. Yields can vary substantially between years due to "biennial bearing", i.e. one "on" year followed by one "off" year. Assuming an apple dry matter content of 13% (Vylupek, 2010), a yield of 12-20 t ha^{-1} equates to a dry matter yield of 1.6-2.6 t ha^{-1}. A yield of 50 t ha^{-1} equates to a dry matter yield of 6.5 t ha^{-1}.
Crop species	Grass species such as perennial ryegrass (*Lolium perenne*)
Crop products	Grass can be grazed directly by livestock or cut to provide animal feed (silage or hay). If the grass is not grazed or cut, then it needs to be mown
Animal species	Sheep
Animal products	The grass can be used to fatten lambs or to maintain the weight of ewes
Other products	None
Regulating services	The trees can promote nutrient cycling and provide shade for the sheep in summer, and shelter in the winter. Sheep eating falling leaves can remove a refuge for fungi infections. The trees will increase carbon storage
Habitat services and biodiversity	Grazing of apple orchards means that poisonous plant species, such as common ragwort (*Senecio jacobaea*), need to be removed from the field.
Cultural services	Grazed orchards may change employment requirements for an orchard
Key references	See end of report

Table 2. Description of the specific case study system

Specific description of site	
Area	3.9 ha
Co-ordinates	51°55’16.8’’ N 2°37’32.3’’W (51.921343, -2.625647)
Site contact	Tobias Lovell
Site contact email	lovelltobias@gmail.com
Example photographs	

Figure 1. Shropshire sheep within the apple orchard in December 2015

Figure 2. An electric fence (left hand side of photo) has been used to divide the orchard into a grazed and ungrazed area (December 2015)

Map of system

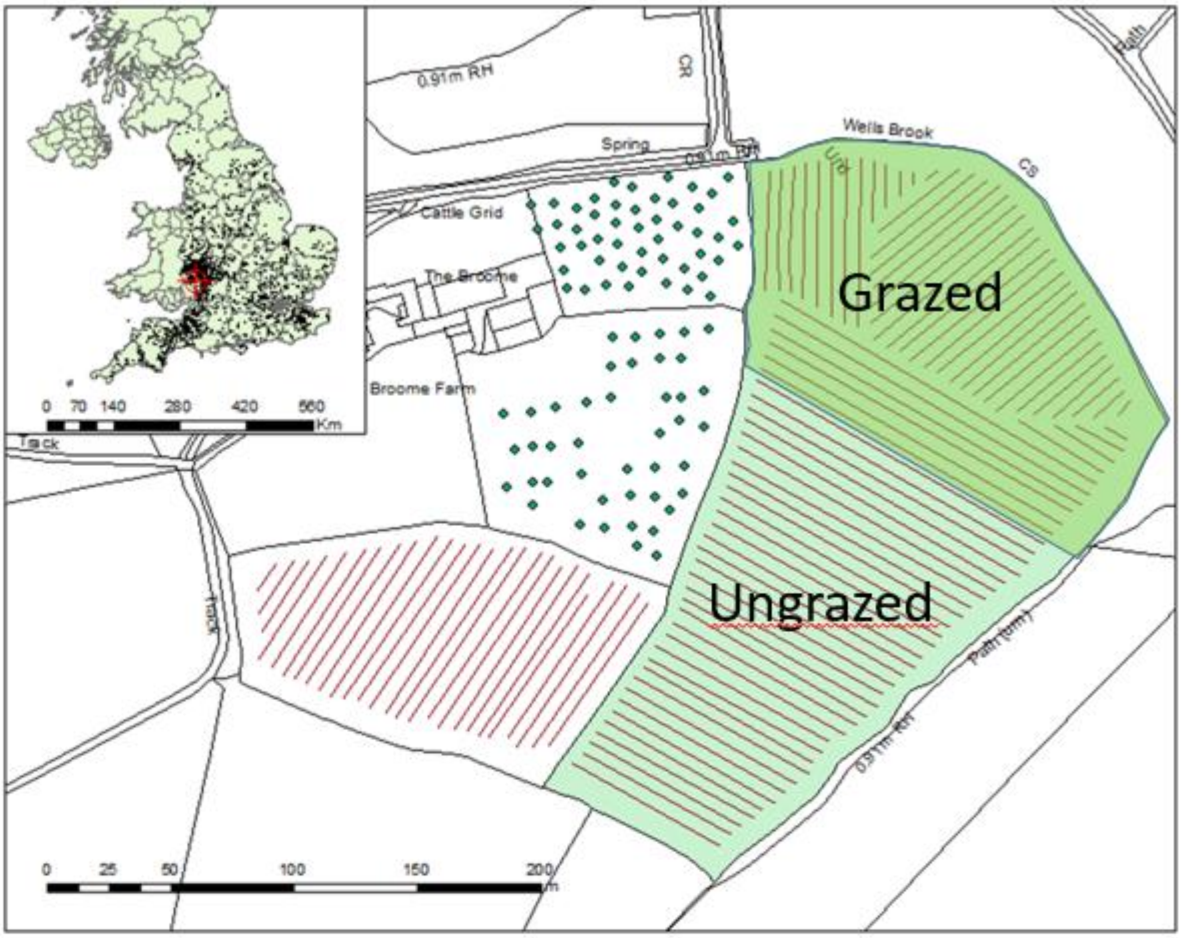

Figure 3. Red lines indicate rows of apple trees in bush orchards, green dots represent individual apple trees in traditional orchards. The trial is based in the area highlighted in green which has been split into a grazed and ungrazed area. © Crown Copyright and Database Right 2014. Ordnance Survey.

Possible modelling scenarios	
Comparison	Technical and economic analysis of grazing v not grazing
Climate characteristics	
Mean monthly temperature	10.22 (± 4.51 SD) °C
Mean annual precipitation	629 (± 181 SD) mm
Details of weather station (and data)	Data from 1960 to 1989 from a number of UK Meteorological Office MIDAS (2015) stations (See Upson et al., 2015).
Soil type	
Soil type	WRB classification: Eutric chromic endoleptic cambisol A cambisol are typified by young soils (as found in much of Northern Europe), which are named from the Latin "*cambiare*" which means "to change" (FAO. 2001). Endoleptic means that the soil rests on continuous rock starting between 50 and 100 cm from the soil surface. Eutric refers to a high level of base saturation.
Soil depth	>120 cm
Soil texture	To be determined
Additional soil	Soils are of the Eardiston 1 (541c) series (NSRI, 2015), described as: 'Well

characteristics	drained reddish coarse loamy soils over sandstone, shallow in places especially on brows'.
Aspect	South-East
Tree characteristics	
Species and variety	Apple (*Malus domestica*) 'Harry Master'
Date of planting	2001
Intra-row spacing	3 m
Inter-row spacing	6 m
Tree density	About 555 trees ha^{-1}
Tree protection	Wire surrounding the tree trunk to a height of 50 cm to protect from rabbits
Pruning	The side branches of the apple trees have been pruned to a height of 1.3 m. Hence this is an orchard comprising "standard" trees; it is not a bush orchard.
Typical apple yield	To be determined
Typical increase in tree biomass	
Crop/understorey characteristics	
Species	Grassland, including perennial ryegrass (*Lolium perenne*)
Management	The grass in the ungrazed orchard was mown in April-May and gain in August 2015 to keep down the grass understory
Typical grassland yield	
Fertiliser, pesticide, machinery and labour management	
Fertiliser	No fertiliser is applied; the field is limed every five years
Pesticides	The apple trees are not sprayed although a problem with Ermine moth (*Yponomeuta malinellus*) was reported
Machinery	Need for tractor access between trees to allow mowing and spraying if required
Manure handling	Not necessary in field
Labour	Sheep need to be checked daily (in terms of checking numbers, health and welfare).
Fencing	To stock-proof the field, the grazing area was fenced using electric fencing.
Livestock management	
Species and breed	Sheep; Shropshire breed. The Shropshire breed are reported by the Shropshire Sheep Breeder Association to be "tree friendly" compared to other sheep breeds (Geddes 2012).
Description of livestock system	The area of the grazed component of the field is about 2.0 hectares. Typically 40 ewes will be kept with one ram. The ewes will conceive in the autumn ("tupping"), with lambing occuring in the spring. On average, each ewe will have 2 lambs. During the weeks immediately before lambing the sheep will be kept indoors. After lambing, the ewe and the lambs will be moved to a field. The lambs will typically be separated from the ewe in late spring. The typical aim is to fatten the lambs as soon as possible ready for market, and to maintain the weight of the ewes until "tupping".
Date of initial entry	The sheep were allowed to enter the site in mid-May 2015; comprising about 40 ewes (20 ewes ha^{-1}) for a 10 week period to 1 August 2015
Date of departure	1 August 2015; an estimated 56 days before the predicted date of apple harvest. The ewes were moved to an alternative 10 hectare grassland site.

Date of second entry	20 ewes added again on 15 December (10 ewes ha^{-1}) and anticipated to stay in the field until February 2016 (prior to lambing in March)
Stocking density	Mid-May to 1 August 2015: 20 ewes ha^{-1}
Animal health and welfare issues	Sheep need to be check daily to ensure health and welfare. During the summer, potential issues include flystrike caused by blowflies (ELANCO, 2015).
Supplementary feed	Sheep are given a mineral bolus
Financial and economic characteristics	
Costs	The apple orchard is owned by a local farmer, and the owner of the sheep is his nephew. The apple orchard receives single farm payment. The estimated cost of the electric fencer was £100 (€129[a]) and the estimated cost for the electric fencing was £200 (€258). A typical annual cost for renting a grass field (known locally as "keep") is about £185 ha^{-1} (€238). A local buyer of apples (Bulmers) is reported to state in their contract that the sheep should be removed 56 days before apple harvest. Hence a key feature of grazing orchards is the requirement for additional areas of grass when the orchard is not available. Grazing orchards was reported by one stakeholder as being "logical but you need additional grassland prior to harvest" Some example costs of apple establishment are provided by Centre for Alternative Land Use (2007). [a] Conversion of pounds sterling to Euros is based on an exchange rate of 1.29 Euros per pound sterling (April 2016)

5 Description of the tree component

The remainder of the report describes the use of a bio-economic model to describe the interrelationship between apple trees and understorey crops including grass.

5.1 Variety

Apple trees for cider production are a combination of a clonal rootstock to give the tree a particular growth habit, and a clonal scion which will determine fruit quality. Most bush orchard systems in Herefordshire are grown on semi-dwarfing rootstock, such as MM 106 or MM 111, which can produce trees about 6-7 m high (Berrie et al. 2010; Vylupek, 2010). The apple variety used at the study site is "Harry Master", which is a "traditional English cider apple variety producing a bittersweet juice" (Orange Pippin Fruit Trees, 2015). Orange Pippin Fruit Trees also report that the variety tends to be harvested "very late in the season", i.e. end of October/November (Lea, 2015).

5.2 Tree density and height

New commercial cider orchards tend to be planted at densities of about 600-700 trees per hectare (Figure 4). Durrant and Durrant (2009) suggest that the cider-maker Bulmers is establishing new orchards planted at a density of 650-750 trees per hectare. Despite this many older orchards are still in use for cider production, and are planted at densities as low as 300 trees per hectare.

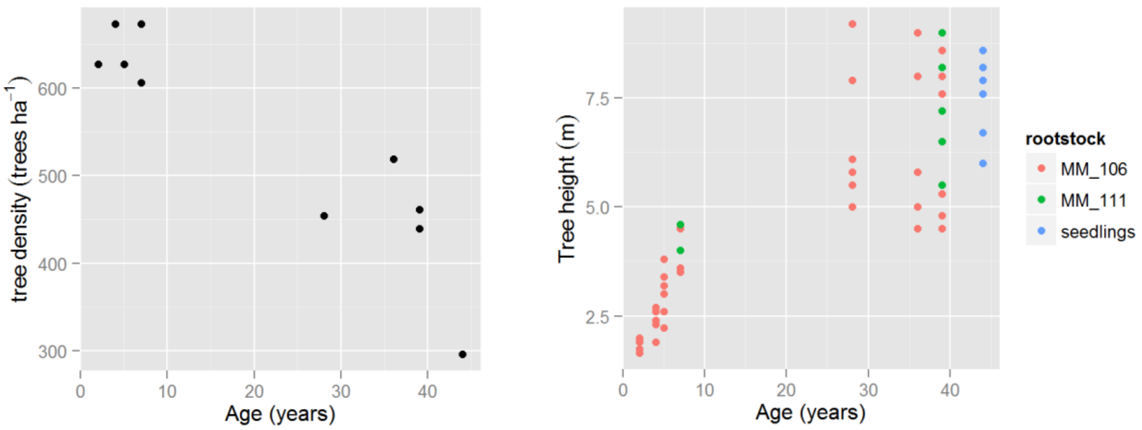

Figure 4. a) Tree density and b) tree height as a function of age in ten cider orchards measured by Vylupek (2010)

The new high density orchards are referred to as 'hedgerow' or 'bush' orchards and are the main system used for cider apple production in the UK (Durrant and Durrant, 2009). The trees in a bush orchard receive early formative pruning to maintain a single dominant leader. This is followed by regular pruning to thin the canopy, enabling an acceptable size of apple to be produced, and allowing sprays to penetrate into the heart of the canopy (Durrant and Durrant, 2009). The adoption of high density bush orchards with small trees (perhaps as low as 2-3 m height) has occurred with the increased mechanisation of apple cultivation including mechanical mowing, harvesting using tree shakers, and pesticide application using air assisted sprayers. The use of small trees allow better control of pesticide application and the potential use of tunnel sprayers to minimise spray drift (Berrie et al. 2010; van de Zande et al. 2014). Vylupek (2010) found that tree height increased from

2-3 m for 5 year old trees, whilst traditional stands of 30-40 year old trees had a height of 4 to 9 m (Figure 4b).

5.3 Relationships between apple yield, and tree size, age and density

A literature search did not reveal extant allometric relationships for apple yield based on tree height, diameter, or crown width. However Vylupek (2010) collected some data on apple fresh weight yields, tree age, and tree dimensions, which were confounded with tree density (Table 3).

Table 3. Summary of data collected by Vylupek (2010). Tree age, density, height, dbh, and apple count are means of measurements taken from three trees.

Field name	Variety	Rootstock	Age (years)	Density (trees ha^{-1})	Height (cm)	D_{bh} (cm)	Apples count
Pad_End	Gilly	MM 106	2	627	198		16
Pad_End	Hastings	MM 106	2	627	177		3
Walk	Gilly	MM 106	4	673	263		44
Walk	Hastings	MM 106	4	673	220		4
Norhans	Gilly	MM 106	5	627	347		73
Norhans	Hastings	MM 106	5	627	261		128
Dry_Marshes	Dabinett	MM 111	7	673	420		246
Long_Field	Dabinett	MM 106	7	606	387		154
Bramley	Dabinett	MM 106	28	454	580	14	608
Bramley	Michelin	MM 106	28	454	737	16	275
Buildings	Dabinett	MM 106	36	519	510	13	115
Buildings	Michelin	MM 106	36	519	867	17	577
Court	Michelin	MM 111	39	439	835	19	357
Court	Summerset	MM 111	39	439	577	18	929
Preston	Dabinett	MM 106	39	461	487	15	772
Preston	Michelin	MM 106	39	461	807	20	739
Norhans	Michelin	Seedlings	44	296	823	23	1005
Norhans	Summerset	Seedlings	44	296	677	22	2346

Seedling rootstocks are not a clonal rootstock, rather apple seeds are planted out, and the most vigorous selected to act as rootstock.

In a discussion about allometric equations for apples at the WP3 workshop in Chalkidiki, it was suggested that the relationship between apple yield and diameter, could be improved by considering tree height, and crown width. Modelling suggests that a slightly better model would also include diameter at breast height (D_{bh}) (Appendix A). A more simple relationship can be produced by relating the number of apples per tree to the cross sectional area of the canopy (Figure 5). It should be noted that the yield per hectare will also depend on the tree density and tree age (Figure 6).

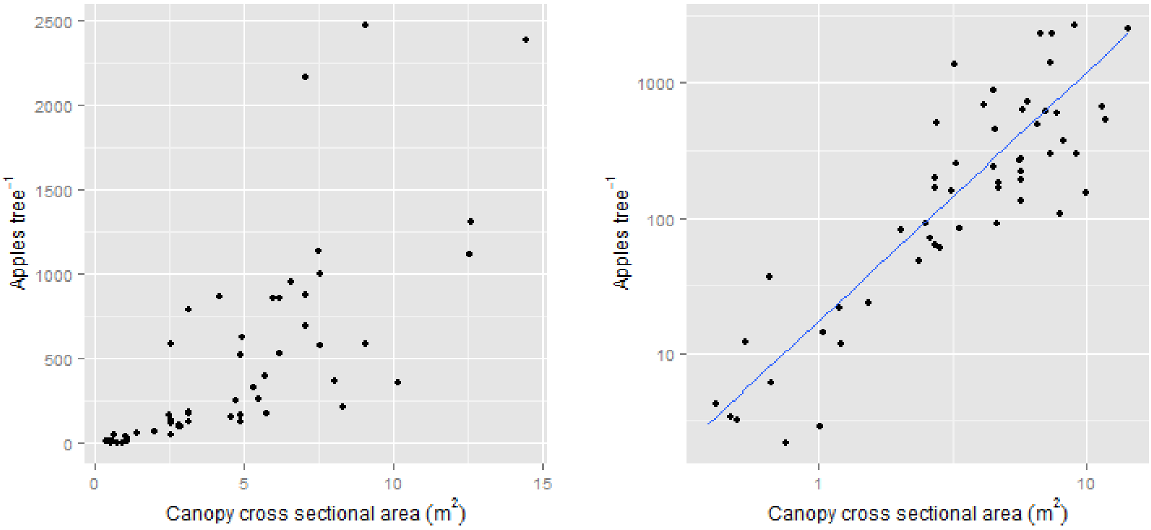

Figure 5: Relationship between apple yield (apple tree^{-1}) and canopy cross sectional area (m^2) on a normal and $\log_{10}$ scale. Regression line follows the equation: $y = 10^{-132.29x^{127.35}}$.

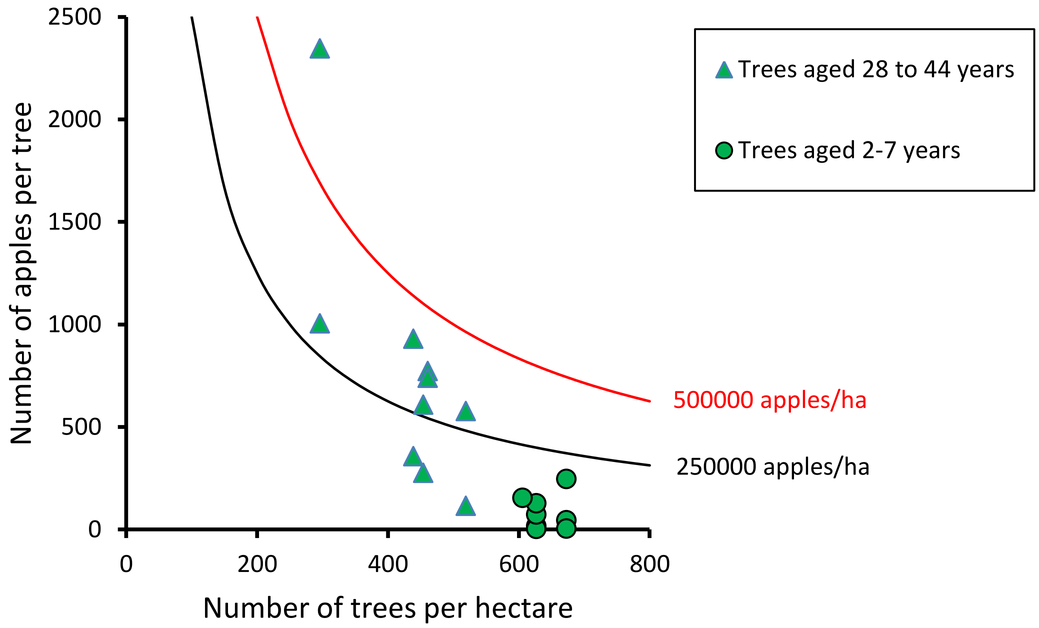

Figure 6. As the number of trees per hectare increases, so the number of apples per tree tends to decrease. Note that the effect of high densities is confounded with young ages in this figure.

5.4 Describing apple yields using the Yield-SAFE model

Vylupek (2010) parameterised the Yield-SAFE model to describe the development of apple yields from planting, assuming the site management characteristics described in Table 4. The site and tree management parameters assumed in the model as described in the thesis and in the model are described in Table 5. Outputs from Vylupek's version of Yield-SAFE are presented in Figure 7.

Table 4. Site management and tree data used to parameterise Yield-SAFE (Vylupek, 2010)

Feature	Average value
Distance between rows (inter-row tree spacing)	599 cm
Tree distance within a row (intra-row tree spacing)	318 cm
Tree strip width	184 cm
Inter-crop width	415 cm
Trees per hectare	525
Rotation	40 years
Proportion of area occupied by crop	70%
Thinning regime	None
Pruning regime	First six years annually then every fifth year
Planting date	January 2 (2)
Pruning date	December 16 (350)
Time of bud burst	May 15
Time of leaf fall	November 6 (310)
Maximum bole height	1.8 m

Table 5. Site and tree management parameters used in Yield-SAFE as reported by Vylupek (2010) and then values as used in a later Yield-SAFE version

Parameter	Unit	Vylupek (2010)	Adjusted
Pruning height increment	m	0.1	**0.01**
Proportion of branch biomass removed per prune		0.1	0.1
Proportion of shoots removed per prune		0.05	0.05
Maximum value of bole height/tree height		0.39	0.39
Maximum bole height	m	1.8	1.8
Number of tree per m^2		0.0525	0.0525
Number of shoots per tree at initial stage	shoots $tree^{-1}$	6	**3**
Biomass of tree at initial stage	g $tree^{-1}$	80	80
Bole height at planting	m	0.6	0.6
Leaf area of tree at planting	m^2 $tree^{-1}$	0.5	0.5
Proportion of biomass to fruit		0.65	**0.5948**
Day of year - fruit set	day of year	150	150
Time of bud burst	day of year	135	135
Time of leaf fall	day of year	310	310
Radiation use efficiency	g MJ^{-1}	0.5626	0.5626
Form factor		0.395	0.395
Water needed to produce 1 g of tree biomass	m^3 g^{-1}	0.00028	0.00028
Fraction of biomass used for respiration maintenance		0.0005	0.00005
Maximum leaf area	m^2	150	150
Wood density	g m^{-3}	750000	750000
Ratio of height to diameter		19	19
Ratio of maximum width to canopy depth		0.6	0.6

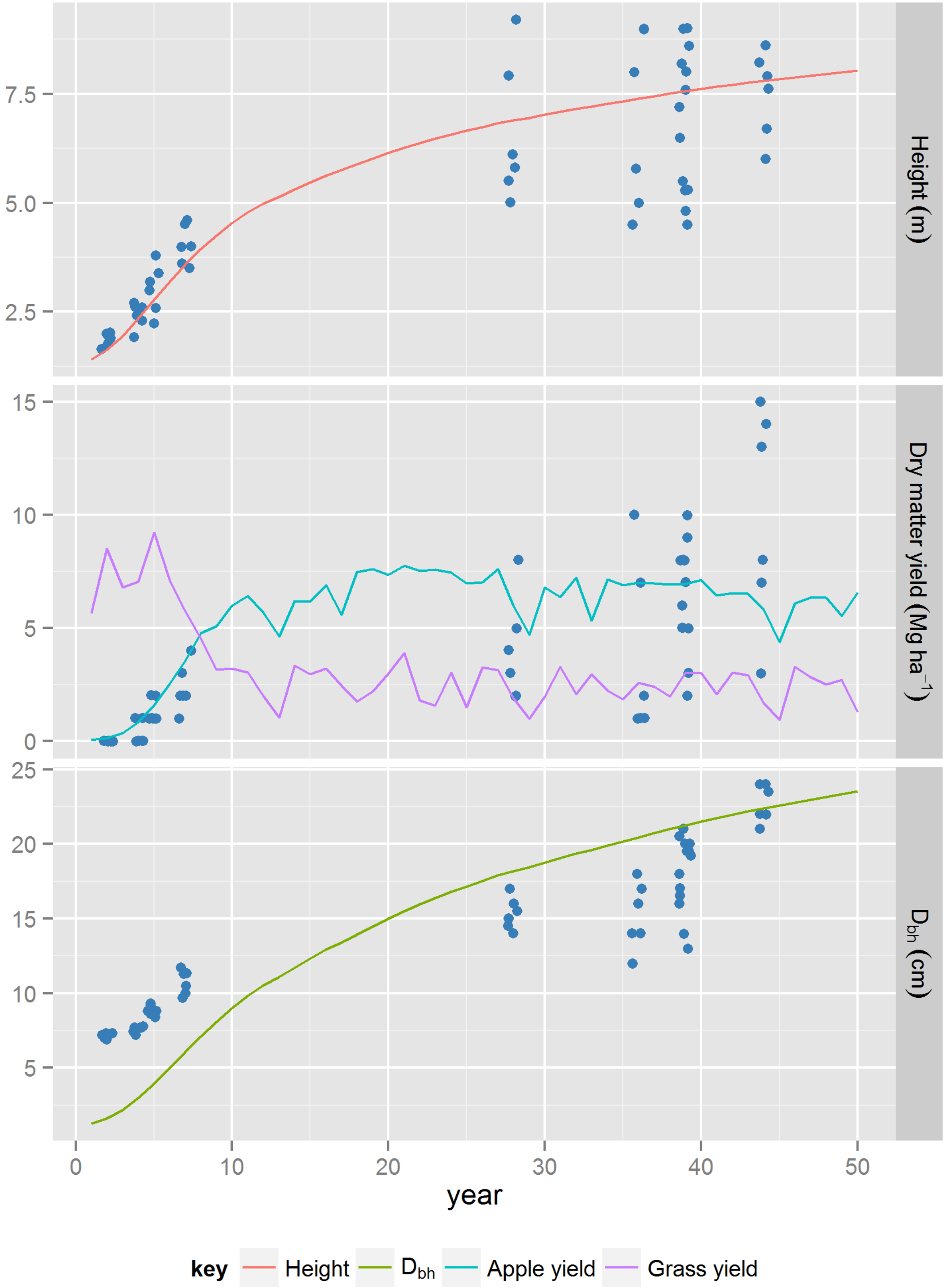

Figure 7. The modelled outputs of tree diameter and height, and apple and grass dry matter using Vylupek's calibration of Yield-SAFE. Data for tree diameter, height and apple yields are also shown. Note that Vylupek did not record D_{bh} of trees which were less than 7.5 cm, so these values have been estimated using the linear relationship between the diameter 20 cm above the graft (D_{20}), and D_{bh}: $D_{bh} = 5.81 + 0.56 \times D_{20}$, R^2=0.85.

5.5 Validating the Yield-SAFE model

Validating the predictions of apple production made by Yield-SAFE is problematic because of the difficulty in obtaining suitable data. However some apple yield data were available from the experimental trials in Loughgall, Northern Ireland. Vylupek's calibration of Yield-SAFE was used, substituting only weather data appropriate for the Loughgall site. Weather data which included solar radiation receipt were not available (although temperature and precipitation values were), so weather data were obtained using the clipick tool (Palma, 2015). Using Vylupek's calibration of Yield-SAFE in comparison with the observed yields from Loughgall suggests that the model may underestimate yields in the early years of growth, whilst beginning to overestimate yields in more recent years (Figure 8). This observation is somewhat at odds with Figure 7 where Yield-SAFE outputs tend to underestimate yields of older trees.

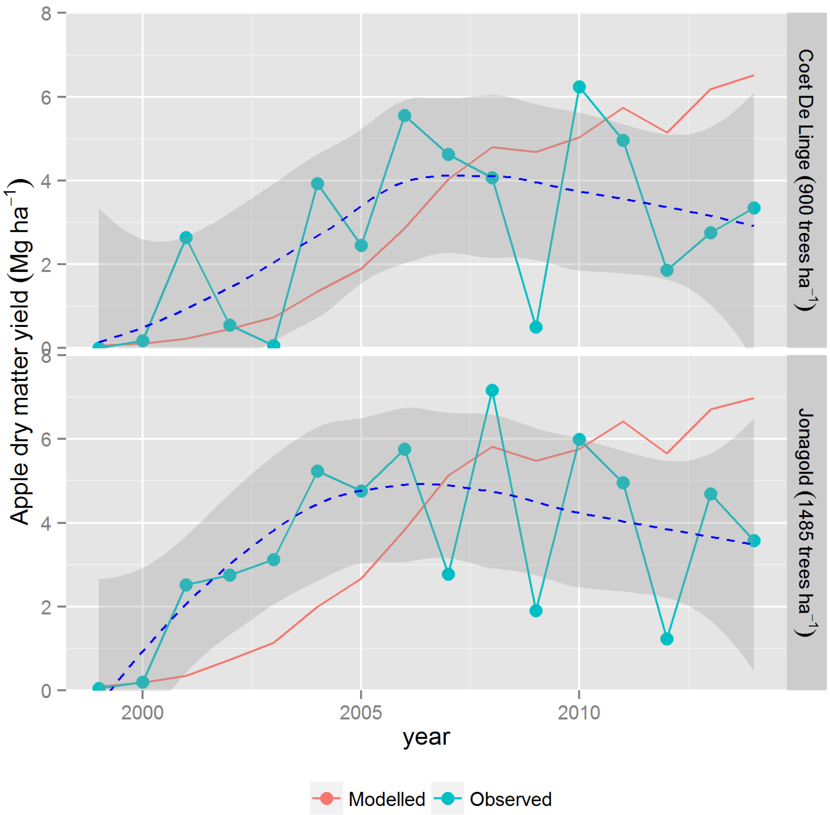

Figure 8. Comparison of observed and modelled yields for two orchards at Loughgall, Northern Ireland. Observed yields have been overlaid with a local polynomial regression with associated standard error shown as the shaded region.

Despite the relative lack of fit, we have not altered Vylupek's calibration which was based on a more comprehensive range of ages compared to the first 16 years at Loughgall. We also note that the validation data are from experimental orchards where the growth regulation treatments may be different from commercial orchards. In addition, the Loughgall orchards had a higher density (900 and 1485 stems ha^{-1}) than the orchards (650-750 stems ha^{-1}) described by Vylupek. In time however, as more data becomes available, it would be advisable to attempt to validate the model outputs again.

6 Reduction in apple yield due to tree mortality

One question regarding grazing cider orchards is the possibility of tree damage by the sheep (Burgess, 2014). As there is little quantitative evidence on the level of harm that sheep may do to trees, we used the Yield-SAFE model to estimate the impact of potential levels of tree mortality. We assumed five levels of mortality increasing from 0% to 4% which we modelled as levels of “thinning” at two year intervals during the first 10 years: (years 2, 4, 6. 8 and 10). Tree mortality was limited to the first 10 years, following the assumption that by this time the trees would be sufficiently robust to survive harassment by sheep.

In general the predicted effects of tree mortality on apple yield and understorey apple yield were small (Table 6; Figure 10). For example, the loss of 210 trees from 525 trees, was predicted to result in 0.31 t ha-1 loss (-5%) in apple yield (dry matter basis). The predicted increase in grass growth was plus 0.24 t ha-1 (+7%). It appears that assuming that the tree loss was uniform, the model assumed that the remaining trees would compensate by producing a larger canopy.

Table 6. Apple and grass yield obtained over 50 years relative to a ‘no mortality’ scenario using Vylupek’s version of Yield-SAFE (525 trees ha^{-1}) and assuming a 1-4% mortality rate without replanting over the first 10 years of orchard establishment. Absolute yields and yields relative to a no mortality scenario are given.

Mortality rate (%)	Tree loss (n)	Apple yield (Mg ha^{-1})		Relative Apple yield (Mg ha^{-1})		Crop yield (Mg ha^{-1})		Relative crop yield (Mg ha^{-1})	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
0	0	5.69	2.03	_	_	3.19	1.85	_	_
1	50	5.66	2.03	-0.03	0.01	3.21	1.85	0.02	0.01
2	100	5.58	2.00	-0.11	0.04	3.27	1.84	0.08	0.04
3	160	5.48	1.98	-0.21	0.08	3.35	1.84	0.16	0.07
4	210	5.38	1.95	-0.31	0.12	3.43	1.83	0.24	0.10

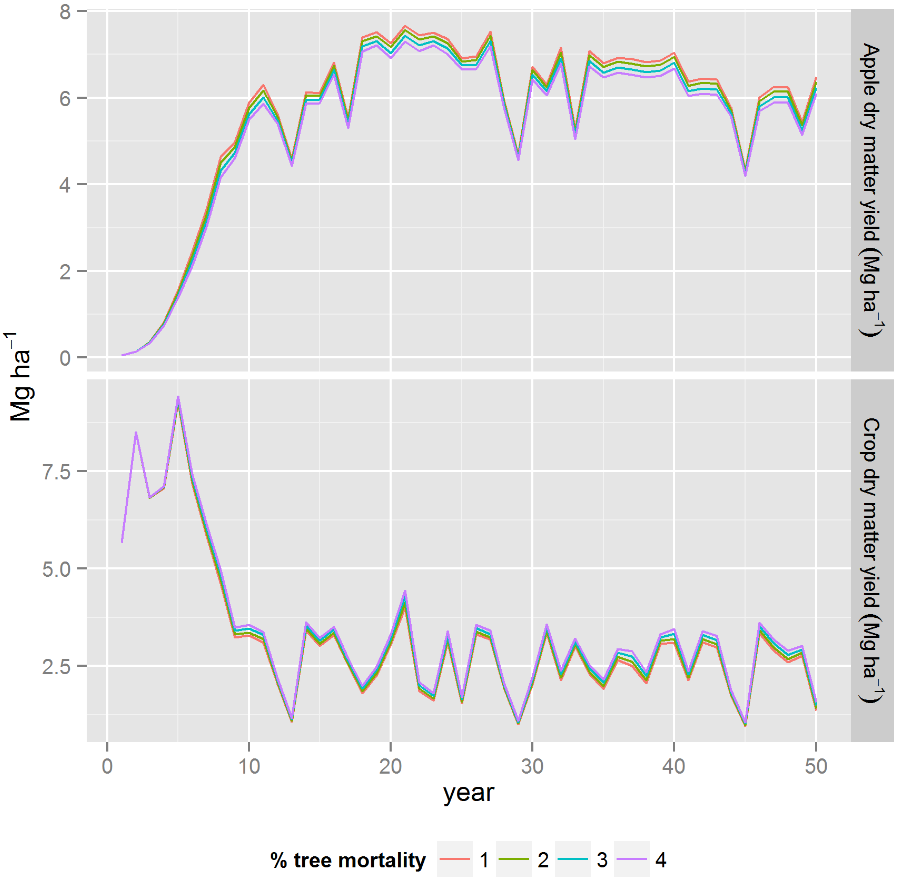

Figure 9. Different scenarios of tree mortality envisaged using Vylupek's calibration of Yield-SAFE, relative to a 'no mortality' scenario. A percentage tree mortality was assumed for the first ten years of growth to reflect damage that might be caused by sheep.

7 Grass component

Assuming that the entire grass area beneath the orchard was grazed, and that this grazing was being substituted for feed (and not grazing on an alternative site), it is possible to put an economic value on the grass yield relative to the cost of buying alternative feed. Graves (pers. communication; August 2015) suggest that grass, when grazed, has an energy value of 11.2 MJ kg^{-1} (dry matter), but only 70% of this is digestible. Multiplying the two gives a metabolisable energy of 7.8 MJ kg^{-1}. Burgess et al (2012) assumed a grass feed value of 9.0 MJ kg^{-1}. Comparing this value to the cost of providing maize fodder allows an economic value to be put on grass grazed within the orchard.

Table 7. Financial value of maize and grass as fodder from Graves (pers. communication 11/08/2015). Values for cut grass are included, however grass from the orchards tends only be grazed.

Feed	Energy content (MJ kg^{-1})	Digestibility (%)	Metabolisable energy (MJ kg^{-1})	Cost if bought (£ Mg^{-1})	Value of fodder (£ MJ^{-1})
Maize fodder	13.2	86	11.35	155	0.01
Grazed grass	11.2	70	7.84	_	_
Cut grass	10.5	80	8.40	_	_

Sheep are not grazed in the orchard throughout the whole year (Burgess, 2014), because of the need to apply pesticides and the requirement by some cider manufacturers that the sheep are removed at least 56 days before harvest. Discussions with the stakeholder group suggested that spraying in the orchards takes place in March and June at about 10 day intervals, and with the apples being harvested between September and November, the main grazing period would be between June and August.

The date of apple harvest varies with variety. If harvest takes place on 30 September, then the sheep would need to be removed from the orchard by 5 August, leaving 65 days grazing from the start of June, this would leave a period of just 35 or 65 days grazing. Note that there is no scientific basis to the 56 day exclusion period, and given that the cider is later pasteurised, it may not be necessary. If this were the case, sheep could be grazed for 121 days. Some example scenarios are presented in Table 8, including the possibility of a variety harvested at the end of August.

Table 8. Summer grazing combinations tested in Yield-SAFE in calendar and approximate Julian days based on the years 1992 – 2042. Grazing was assumed to start on 1 June (Julian day 152)

Scenario	Grazing ends	Pre-harvest Exclusion	Harvest	Duration (days)
Early no exclusion (EY NOEX)	31 August (243)	_	31 August (243)	91
Late yield no exclusion (LY NOEX)	30 Sept (273)	_	30 Sept (273)	121
Early yield exclusion (EY EX)	6 July (188)	56 days	31 August (243)	36
Late yield exclusion (LY EX)	5 August (217)	56 days	30 Sept (273)	65

7.1 Estimated value

The value of the grass was derived from the Yield-SAFE model assuming the grass yield up to the day when grazing ends and the fodder costs assumed in Table 7 (Figure 10 and Table 9). Assuming that grass as a substitute for maize feed, the various grazing scenarios, and there was no tree mortality, resulted in an average annual grass feed value of £108-121 ha^{-1} (€139-156 ha^{-1}) (Table 9). Note that these values are given over a period of 40 years, and annual variation in grass production results in a lower extreme of £40-46 (€52-59) and an upper extreme of £158-192 (€204-250) depending on the grazing scenario (Figure 10). Note that these values are given over a period of 40 years, and annual variation in grass production results in a lower extreme of between £40 and £46 (€52 and €59) and an upper extreme of between £158 and £192 (€203 and €248) depending on the grazing scenario (Figure 10). Total grass production under a no mortality scenario was 3.19 ± 1.85 Mg ha^{-1}, and 3.43 ± 1.83 Mg ha^{-1} assuming 4% annual mortality.

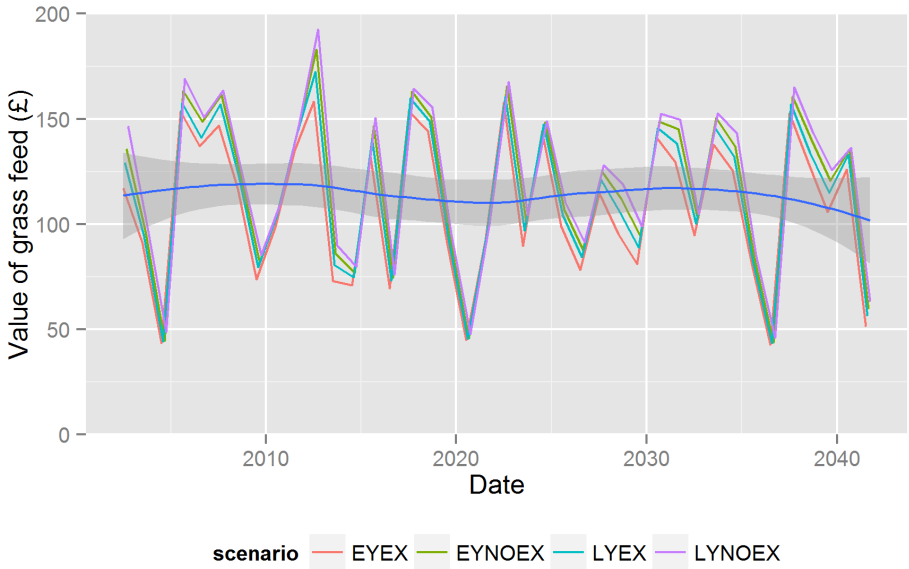

Figure 10. Annual variation in the value of grass feed relative to the cost of buying maize fodder using Vylupek's calibration of Yield-SAFE. The grazing scenarios presented in Table 8. The trend line represents a local polynomial regression (LOESS), and associated standard errors as the shaded region. The first ten years of growth (1992-2002) have been excluded.

Table 9. Estimated annual yield of available grass and associated feed value within a "mature" orchard system (i.e. more than 10 years) assuming zero or 4% annual tree mortality in the first 10 years.

Annual tree mortality	Grazing scenario	Available grass ($Mg\ ha^{-1} a^{-1}$)		Feed value ($£\ a^{-1}$)	
		mean	SD	mean	SD
0%	EYEX	1.38	0.44	108	34.4
0%	EYNOEX	1.50	0.47	117	37.0
0%	LYEX	1.45	0.46	114	35.7
0%	LYNOEX	1.54	0.48	121	37.5
4%	EYEX	1.47	0.46	116	36.0
4%	EYNOEX	1.65	0.51	129	39.8
4%	LYEX	1.58	0.48	124	37.9
4%	LYNOEX	1.71	0.52	134	40.7

7.2 Limitations to the grass model in Yield-SAFE

At present Yield-SAFE simulates grass growth as if it were any other crop. It begins to grow once a temperature threshold is reached (5°C), and stops growing on a specified day (300). If this day of harvest were removed, we would expect grass growth to more or less follow the solar radiation receipt and a more or less Gaussian curve. In practice grass growth can predominantly occur in the spring as stores of carbohydrates, built up during the winter, are repartitioned in a spring flush of growth (Figure 11).

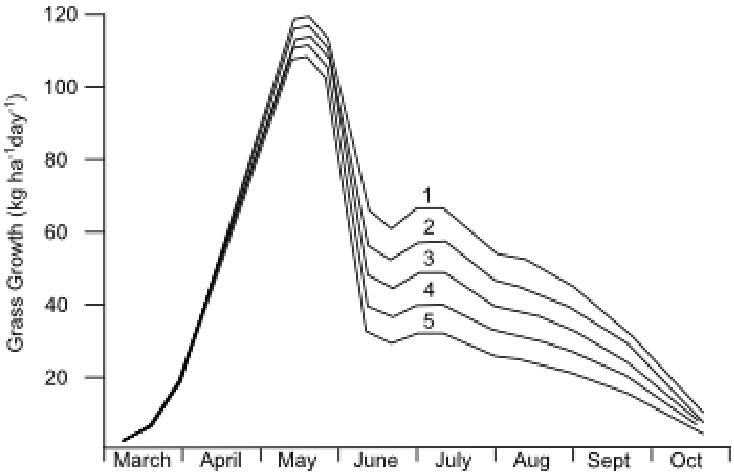

Figure 11. Seasonal pattern of dry matter production from a perennial ryegrass sward at five site class, reproduced from Corrall et al. (1990)

The current growth pattern of grass within Yield-SAFE does not account for this distribution (Figure 12). However as the simulation progresses, grass growth begins to resemble the pattern shown in Figure 11 due entirely to competition for resources with the trees as they increase in size. All else being equal, this observation suggests that grass yields may be underestimated before and during the onset of grazing, in the current way that grass growth is implemented in Yield-SAFE.

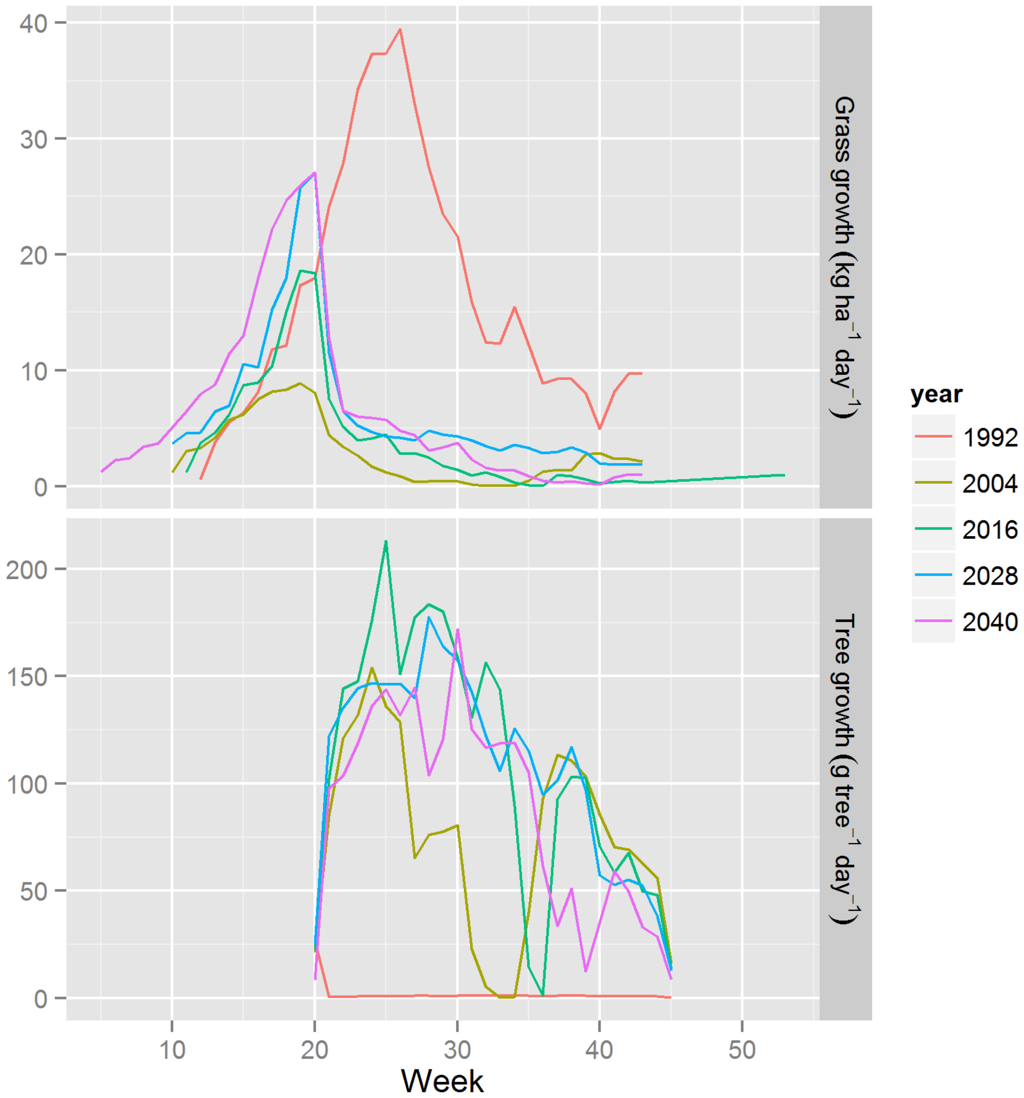

Figure 12. Average daily dry matter production (presented per week) in Vylupek's model (50 years) for both grass and apple trees. The steep decline in grass growth in later years correlates with the onset of tree growth.

8 Acknowledgements

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Appendix A: Allometric equation for apple production

One potential issue with including D_{bh} is that Vylupek's data included a large number of missing D_{bh} values. It is unclear why these values are missing, but where D_{bh} values are missing, diameter at 20 cm above the graft (D_{20}) is available, and a strong relationship between the two exists. Hence two methodologies were tried to deal with these missing values. The first was to establish a linear relationship between D_{20} and D_{bh} and to use this to predict the missing D_{bh} values. The second was to train the model having removed training examples for which missing values were present. The latter did not prove to be an effective strategy, and the results of this are not presented here.

Table 10. Maximal models specified before simplification where yield = number of apples per tree, *cwidth* = crown width, and *bheight* = unbranched bole height. All units in cm. In this formula specification × should be read as 'all interactions of'.

Model	Formula
Without D_{bh}	$\log_{10} yield = \log_{10} height \times cwidth \times bheight$
With D_{bh}	$\log_{10} yield = \log_{10} height \times \log_{10} dbh \times cwidth \times bheight$

Maximal models used at the start of modelling are included in Table 1; these were successively simplified based on Aikake's Information Criterion corrected for small sample sizes (AICc) and successive F-tests following the approach laid out by Johnson and Omland (2004). The final simplified models are presented in Table 11, whilst the models fits relative to the three input features are presented in Figure 13.

Table 11. Formula developed from minimum adequate models to predict apple yield (apples $tree^{-1}$) and associated Aikake's Information Criterion corrected for small sample sizes (AICc)

Model	Formula	AICc
Without D_{bh}	$yield = 10^{\log_{10} height + cwidth + \log_{10} height \times cwidth}$	20.95
With D_{bh}	$yield = 10^{\log_{10} height + \log_{10} dbh + cwidth + \log_{10} height \times \log_{10} dbh}$	2.78

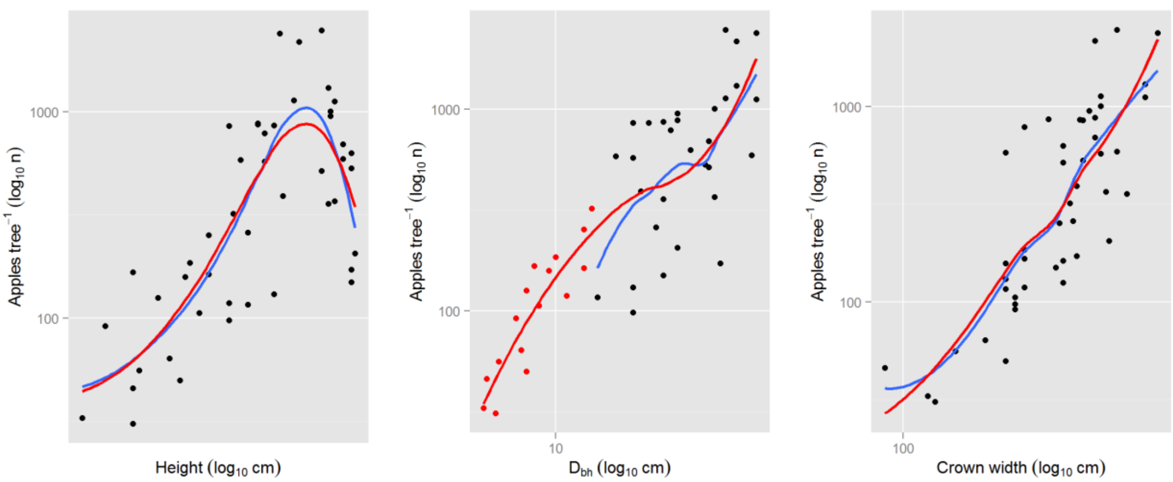

Figure 13. Data from Vylupek (2010) showing apple counts per tree as a function of height, D_{bh}, and crown width, all on a $\log_{10}$ scale. Lines show a locally weighted polynomial regression (LOESS) applied to the actual data (blue), and to estimates of apple yield based on the original explanatory

variables (red). Red points in the D_{bh} plot have been estimated from measurements of diameter 20 cm above the graft (D_{20}).