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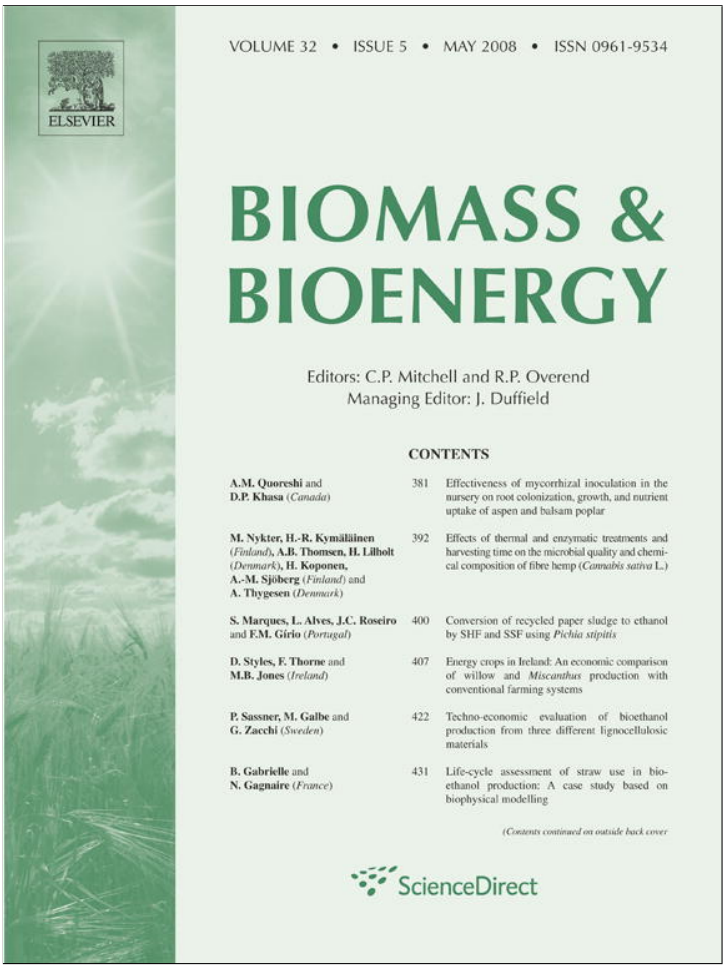

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Energy crops in Ireland: An economic comparison of willow and *Miscanthus* production with conventional farming systems

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ABSTRACT

Recent full decoupling of EU agricultural subsidy payments from production in Ireland is forecast to result in substantial destocking of grassland over the coming decade. In conjunction with increased energy prices, this presents new opportunities for energy crops. This paper uses extensive literature review and country-specific information on current prices to construct life-cycle cost assessments for production of *Miscanthus* and short-rotation coppice willow (SRCW) in Ireland. Gross margins for different harvest and supply strategies (e.g. chopped or baled harvest for *Miscanthus*; stick or chipped harvest for SRCW) are calculated based on farm-gate biomass prices equivalent to 70, 100 and 130 € t^{-1} dry matter (DM) at maximum 20% moisture content—reduced for some SRCW supply strategies to reflect additional chipping and transport costs, and lower heating values. These are compared with gross margin projections for conventional agricultural systems (dairy, cattle rearing, 'cattle and other', sugar beet, winter wheat, spring barley and set aside) using a net present value approach. Production costs expressed per tonne DM were similar for *Miscanthus* (€37–48) and SRCW (€31–46). Mid-estimate discounted, annualised gross margins ranging between 326 and 383 € ha^{-1} for *Miscanthus*, and between 211 and 270 € ha^{-1} for SRCW, compared favourably with all conventional agricultural systems considered except dairy. These gross margins were based on peak-productivity combustible yields of 14 and 10 t DM ha^{-1} a^{-1} for *Miscanthus* and SRCW. Yield variation will affect gross margins, but low yields were still calculated to realise positive returns. However, the application of high-activity cost estimates for all energy-crop cultivation activities resulted in negative returns for some supply strategies. Recently announced government support for SRCW and *Miscanthus* considerably reduces investment risk for farmers, whilst utilisation of SRCW to treat waste water could substantially increase revenues. Energy crop cultivation has the potential to offer farmers a modestly profitable alternative to declining returns from conventional land uses.

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1. Introduction

In 2004, Irish greenhouse gas (GHG) emissions were 25% higher than 1990 levels [1], significantly exceeding Ireland's Kyoto Commitment to a maximum GHG emission increase of 13% above 1990 levels over the 2008–2012 commitment period. As a consequence, Ireland will be required to pay hundreds of millions of euro, either in penalties or towards GHG emission reduction schemes in developing countries. Of the 68.5 Mt carbon dioxide equivalents (CO_2 eq.) emitted in Ireland in 2004, 28% were attributable to agriculture [1]. This reflects the large agricultural land area (4.3 M ha) relative to population size (4.24 M people), and the dominance of livestock production within the agricultural sector [2]. Grassland supporting sheep and cattle systems account for 83% of agricultural land area [2] and result in the emission of the potent GHGs methane and nitrous oxide. Approximately 22% of 2004 GHG emissions were attributable to electricity production, and a further 22% to the heating of domestic, commercial and public buildings [3]. Styles and Jones [4] demonstrate the substantial national GHG emission savings possible through the co-firing of energy crop biomass in existing peat and coal power stations, accounting for both displaced livestock production and substituted coal and peat electricity production. Similar savings are possible through the utilisation of energy crop biomass for heating [5].

Recently in the republic of Ireland, the debate regarding the future role of energy crop production has heightened in direct response to a number of issues. Firstly, in response to the reform of the EU Common Agricultural Policy (CAP), Ireland replaced production-indexed farm subsidies with production-'decoupled' single farm payments (SFP) in 2005, based on land area farmed during 2000–2002. Economic modelling of farm-level response to this decoupling of direct payments has indicated that livestock numbers will decline significantly (i.e. 21% reduction in dairy cows; 10% reduction in non-dairy cattle; 26% reduction in sheep numbers from 2002 to 2012 [6]). The land areas dedicated to both cereal production and sugar beet (in response to a reduction in EU sugar-beet price support) are also forecast to decline [7,8]. Secondly, dramatic increases in oil and gas prices have recently made fossil-based electricity and heat production substantially more expensive. These high prices may reflect a new era of higher energy costs perpetuated by limitations in the rate of oil supply and rapidly increasing demand from the growing economies of China and India. Thirdly, the introduction of the EU Emission Trading Scheme (ETS) in 2005, with future CO_2 allowances trading at approximately €15 t^{-1} CO_2 for 2008 [9], will further increase the costs incurred by large-scale fossil-fuel combustion, and provide financial incentives for carbon-neutral fuels, including biomass, under the EU ETS legislation [10,11]. The competitive economics of *Miscanthus* co-firing in peat power stations, and willow wood chip heating in domestic and small-commercial dwellings, are outlined in [12].

One key determinant of whether Ireland will fully respond to the aforementioned drivers for change is the presence of a strong and apparent economic incentive for farmers to become producers of energy crops. Deurwaarder [13] identified uncertainty regarding the cost effectiveness of biofuel production in Europe as one of the major impediments to the development of the sector. There has been no published research on the comparative economics of energy crop production in the republic of Ireland in the recent past. Without some assessment of the economic value of these crops, the future development of bioenergy crops in this region remains uncertain. While similar studies have been undertaken in other countries [14–16], and in N. Ireland [17,18], there is significant scientific merit in establishing work that will specifically determine the potential role of indigenous energy crop production in the republic of Ireland. Hence, this paper explores the current economic outlook for the production of energy crops in Ireland, particularly considering competitiveness with conventional agricultural land uses. The energy crops considered are the fast-growing and high-yielding short-rotation coppice willow (SRCW) and *Miscanthus* × *giganteus* (also referred to as Elephant grass). As of early 2007, these crops became eligible for new government planting and maintenance subsidies (detailed below) [19].

2. Methodology

2.1. Life-cycle cost assessment

Life-cycle cost assessments for 23-year, 7-cut SRCW, and 16 year, 14-cut *Miscanthus* plantations were conducted, based on the farm operation sequences shown in Table 1, and for each of the supply strategies listed in Table 2. Costs for each activity were taken from the literature, and converted to 2006 prices (Table 3) using inflation rates for agricultural inputs up until 2004 [2], and FAPRI-Ireland projections for variable-cost inflation thereafter (Fig. 1). This ensured accurate comparison with FAPRI-Ireland projections for conventional agricultural system gross margins after 2004. Activities outlined in Table 1, and yields outlined in Table 4, are identical to those applied in a previous paper [4], in which life-cycle analysis was used to identify the GHG emission reductions possible through *Miscanthus* and SRCW utilisation.

Fertiliser application rates of 100:20:100 kg ha^{-1} a^{-1} N:P:K were used for *Miscanthus*, following maximum rates suggested by [20]. This covers the crop off-takes of 88, 11 and 95 kg N, P and K per hectare in 13.5 t dry matter (DM) stems as calculated by [21], and is greater than the 80, 10 and 60 kg ha^{-1} a^{-1} replenishment rate used by [22]. Also shown in Table 3 is an estimate of cultivation costs based on new contracts provided by the first Irish agricultural contractor to specialise in *Miscanthus* [23]. They 'guarantee' both successful establishment for a cost of €2470 ha^{-1} to the farmer, and a crop price of approximately €50 t^{-1} at up to 20% moisture content (€63 t^{-1} DM). *Miscanthus* plantations may maintain high productivity for up to 20 years after planting [20,24], but the conservative assumption of a 15-year productive lifetime was applied here (Table 1). Herbicide application on established SRCW plantations is highly dependent on local circumstances, and in many instances may not be necessary due to rapid canopy closure once the crop is established, and the beneficial effect of some ground cover. Here, it was assumed that worst-case scenario herbicide costs of €75 ha^{-1}

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Table 1 – Life cycle activities for SRCW and *Miscanthus* cultivation, as applied to LCA in [4], and to life-cycle cost assessment in this paper

Year	SRCW	Year	*Miscanthus*
0	Herbicide application Subsoiling and ploughing	0	Herbicide application Subsoiling and ploughing
1	Herbicide and insecticide (leather jacket control) application Lime application (3 t ha^{-1}) Soil rotovation Planting using a step or cabbage planter at density of 15,000 cuttings per ha	1	Fertiliser application (67, 13 and 67 kg ha^{-1} N, P and K) Lime application (3 t ha^{-1}) Soil rotovation Planting, potato planter at density of 20,000 rhizomes per ha Rolling
2	Coppice Fertiliser application (128, 28 and 178 kg ha^{-1} N, P and K) Herbicide application	2	Herbicide application Fertiliser application (67, 13 and 67 kg ha^{-1} N, P and K)
5	Stick/chip harvest late winter (i.e. winter year 4/5) Drying[a] Storage on farm[b] Fertiliser application (192, 42 and 267 kg ha^{-1} N, P and K) Herbicide application[c]	3–15	Cut and bale/chop harvest late winter Drying[a] Storage on farm[b] Repeat year 2, but apply fertiliser at 100:20:100 kg ha^{-1} N, P and K from year 4 onwards
8	Late winter harvest (i.e. winter year 7/8) Drying[a] Storage on farm[b]	16	Apply herbicide to new growth and plough
9–22	Repeat year 5–8 rotation 5 more times		
23	Remove stools		

[a] Drying depends on harvest method, storage and end use.
[b] Storage dependent on harvest method and end use.
[c] Assume every other rotation.

Table 2 – Harvest and supply strategy abbreviations and descriptions for SRCW and *Miscanthus*

	SRCW				*Miscanthus*		
	S1	S2	C1	C2	C	B	A
Harvest	Stick	Stick	Chip	Chip	Chopped	Baled	Chopped, delayed
Storage	Outdoors, covered	Outdoors, covered	Shed	None	Outdoor, covered	Outdoor, covered	None
Drying	Natural	Natural	Forced, heating	None	Natural	Natural	Delayed harvest
Process	Chip on farm	Bundle	None	None	None	None	None
Supply	Dried chips	Dried sticks	Dried chips	Wet chips	Dried, chopped	Dried bales	Semi-dry, chopped

are incurred every other harvest cycle [25]. Herbicide application is considered necessary only in the establishment year for *Miscanthus*, as leaf-litter ground cover and rapid canopy closure were assumed to suppress weed growth [21].

The 2006 cost estimates shown in Table 3 include low-, mid- and high-cost estimates for each activity, representing the range of values found in the literature. These were used to generate low-, mid- and high-production cost estimates, denoted by the suffices '*a*', '*b*' and '*c*', respectively, applied to supply strategy labels (e.g. S1b refers to mid-cost stick harvest and supply). The most appropriate values were chosen for the 'mid-cost' estimates, based on similarity to Irish circumstances and contemporaneousness. In some instances, it was possible to find only one or two values for specific activities in the literature, or values that included certain fixed costs, such as shed construction and rent, not considered here (see Section 4.1). 'Mid-cost' estimates were thus sometimes at the lower or upper extreme of the quoted literature range, but were considered by these authors to be the most realistic costs. It is clear that there is a wide variation in cost estimates for some activities. Rabbit fencing may be required for SRCW if there are large rabbit populations in the area, and this is considered in the 'high' establishment cost estimate (Table 3). A high degree of certainty may be associated with establishment costs based on data from Rural Generation and the *Miscanthus* contractor [23], who base their

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Table 3 – Costs (adjusted to 2006 prices) associated with each of the activities outlined in Table 1, based on mid-cost estimates from the literature and maximum yields of 12 and 20 t ha^{-1} a^{-1} for SRCW and *Miscanthus*, respectively

Activity	SRCW (€ ha^{-1})				*Miscanthus* (€ ha^{-1})		
	Stick, store, chip	Stick, store	Chip, dry, store	Chip	Chop	Cut and bale	Contractor
Establishment			2736 [25] 1500–3215			2470 [42] 1060–2555	2470
Fertiliser app.			336 [2] 274–494			161 [2] 80–241	161
Herbicide app.			80 [25] 31–80			31 [25] 31–80	31
Harvest	682 [43] 514–1056	682 [43] 514–1056	417 [15] 140–541	417 [15] 140–541	237 [27] 233–237	389 [27] 315–389	237
Dry+store	24 [26] 0–948	24 [26] 0–948	701 [26] 455–948	n/a	110 [27] 28–261	48 [27] 48–141	0
Chipping	243 [32] 112–524	n/a	n/a	n/a	n/a	n/a	0
Removal			517 174–1864			207 154–259	207

The ranges of low to high cost estimates from the literature are also displayed beneath. *Miscanthus* costs based on contractor establishment and immediate off-take are displayed on the right.

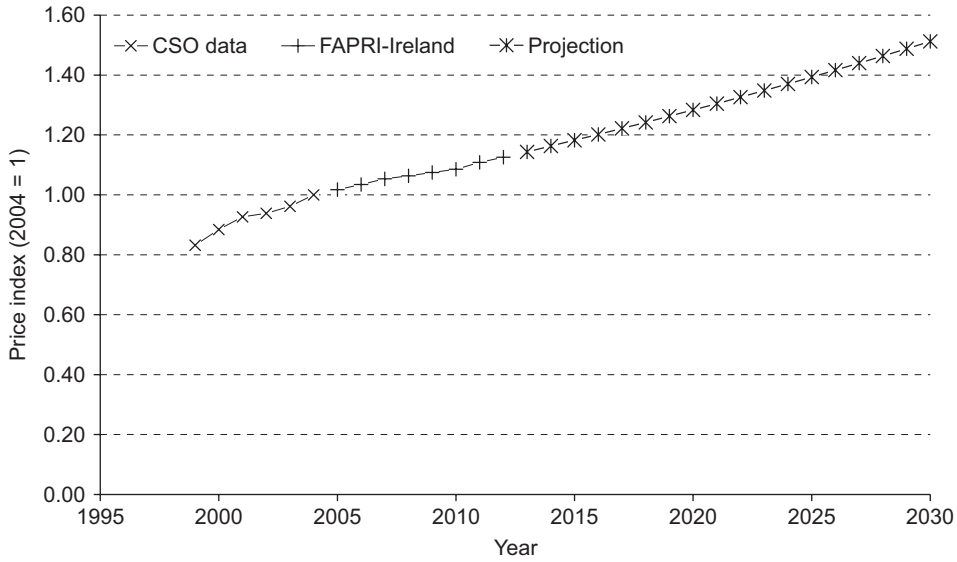

Fig. 1 – CSO, FAPRI-Ireland, and projected price inflation applied to model (*Source*: [2,6]). Projections based on 3-year rolling average extrapolated from FAPRI-Ireland data.

business practice on these costs. In fact, the *Miscanthus* establishment cost quoted by [23] is identical to (and perhaps based upon) the 2006-inflated DEFRA cost estimate. Fertiliser costs, based on average fertiliser prices quoted by [2], are also reliable. In contrast, drying and storage costs varied widely in the literature, depending on the techniques/equipment used and assumptions made in the cost calculations (discussed later), and these were associated with the greatest uncertainty. Fixed shed costs were not included in wood chip storage costs here, and outdoor storage of stick-harvested SRCW and *Miscanthus* under plastic sheeting was assumed [26], for an average of 9.5 months.[1] *Miscanthus* storage costs of €48 and €110 ha^{-1} a^{-1} for baled and chopped material [27], were high compared with SRCW storage costs of €24 ha^{-1} a^{-1} [26], but this may be representative of higher yields and less

[1] Assume at least 6 months required to bring moisture content down to less than 20%, based on [37].

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Table 4 – Low, mid and high annualised yield assumptions for SRCW and *Miscanthus*

Yield level	SRCW (t DM ha^{-1} a^{-1})		*Miscanthus* (t DM ha^{-1} a^{-1})	
	Standing	Combust.	Standing	Combust.
Low				
Av. 1st cut (s)	4.0	3.4	9.3	6.5
Subsequent	6.0	5.1	14.0	**9.8**
Plantation av.	5.2	4.4	11.7	8.2
Mid				
Av. 1st cut (s)	8.0	6.8	13.3	9.3
Subsequent	12.0	10.2	20.0	14.0
Plantation av.	10.4	8.8	16.7	11.7
High				
Av. 1st cut (s)	9.3	7.9	17.3	12.1
Subsequent	14.0	11.8	26.0	18.2
Plantation av.	12.2	10.3	21.7	15.2

Yields are divided into those for the first cut (year 4) for SRCW and an average of the first 2 cuts (years 2 and 3) for *Miscanthus*, subsequent maximum annual yields, and plantation lifetime average.
Standing yields refer to above-ground biomass productivity.
Combustible yields refer to net, exportable biomass after harvest and storage losses.

favourable handling/storage properties of *Miscanthus*, so they were applied.

2.2. *Ex ante methods for comparing the economics of energy crops with traditional farming systems*

From the costs listed in Table 2, an economic spreadsheet model, based in Microsoft Excel, was used to evaluate the life-cycle economics of SRCW and *Miscanthus*. A net present value (NPV) approach was adopted, similar to that presented by [28], in which the two perennial energy crops considered were converted to an annual income stream, enabling a comparative economic analysis with competing conventional farming systems. Total costs and returns for the two energy crops over their 16 and 23 year plantation lifetimes were calculated as NPV for the year of plantation using a 5% discount rate, annualised, and expressed per hectare. Where literature values were expressed per t DM they were converted to per hectare costs based on DM yield scenarios set out in Table 3. For *Miscanthus*, leaf senescence, harvest and storage losses were estimated at 30% of DM [29,30], whilst for SRCW, harvest and storage losses were estimated at 15% (though this will vary according to harvest, drying and storage methods [26]). Within each cost level, the model varied fertiliser input, harvest, drying and storage costs in proportion to yield. A number of harvest and supply routes were considered—if energy crops are to continuously supply heat and power generation throughout the year, a range of harvest strategies may be required depending on the time period between harvest and combustion, and the method of combustion [26]. Unless otherwise stated, the main results presented are based on the 'mid-cost' estimates.

In the absence of well-defined markets for energy-biomass in Ireland, with only a pioneer market for wood fuels, the price farmers could expect to receive for energy crop biomass is uncertain, though likely to benefit from recent increases in energy costs. The *Miscanthus* contractor is offering a guaranteed price of approximately €50 t^{-1} of *Miscanthus* at up to 20% moisture content (~€63 t^{-1} DM), and this value is applied to the contractor scenario. Once a demand is established for biomass in Ireland (discussed later), prices may be expected to increase above this value. Here, we have assumed identical prices for *Miscanthus* and wood chips, at 70, 100 and 130 € t^{-1} DM for low, mid and high estimates. These prices are in line with the delivered price of moist wood chips quoted by Rural Generation in Northern Ireland (~€100 t^{-1} DM), and the current wood pellet price of approximately €168 t^{-1} DM in the republic of Ireland [31], considering pellets contain 20 GJ t^{-1} DM energy compared with 18 GJ t^{-1} DM for wood chips at 20% moisture content, and their superior convenience. In the S2 supply strategy, where the farm-gate product is bundled sticks rather than chips, the price of the wood is reduced by €5 t^{-1} DM over the price range considered (i.e. farm-gate prices of €65, €95 and €125 t^{-1} DM). This accounts for the additional cost of (more-efficient) centralised chipping incurred by the consumer (based on the 2006-adjusted prices of €3.52 t^{-1} DM quoted by [26], and €7.68 t^{-1} DM quoted by [32]). Similarly, in the C2 supply strategy, where wet chips are sold immediately after harvest, the price received for them is reduced by the additional transport cost (~€3.24 t^{-1} DM, over 50 km) and according to their lower net heat of combustion.[2] Thus, farm-gate prices of 60, 87 and 115 € t^{-1} DM are applied to C2 supply strategy gross margin calculations. This was done in an effort to normalise farm-gate prices for SRCW, so that a standard product of chipped, dried (max 20% moisture content) wood was being compared among supply strategies.

Energy crop NPVs were compared with gross margins calculated for traditional farming systems in the republic of

[2] LHV of 16.4 GJ t^{-1} DM at 50% MC compared with 18.1 GJ t^{-1} DM at 20% MC [35].

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Ireland; namely specialist dairy farms, specialist beef rearing farms, specialist other beef farms, and sugar beet, spring barley, winter wheat and set aside, as defined by the Teagasc National Farm Survey (NFS). The most up-to-date version of this survey [33] presents 2004 values, but gross margins have been extrapolated up to 2012 in the FAPRI-Ireland model [7,34] based on predictions of the response to the new, decoupled subsidy scheme (Fig. 2). Unfortunately, farm-level FAPRI-projections for sheep farming could not be obtained, and this land use is therefore omitted from the comparison despite its probable high potential for substitution in Ireland. In 2005, there was a large decrease in gross margins associated with each agricultural system, reflecting the decoupling of subsidy payments from production (Fig. 2). The area-based SFP is activated simply by 'farming' the 2000–2002 reference land area in accordance with 'good environmental practises', and so would also be received by farmers growing energy crops. Therefore, this subsidy is not considered in the calculations here. However, the energy-crop-specific EU subsidy of €45 $ha^{-1} a^{-1}$ is considered in the energy crop NPV, as it is activated only by growing energy crops. The CAP also enables farmers to sustain set-aside payments (though not the €45 $ha^{-1} a^{-1}$ subsidy) on set-aside land used for energy crops, so financial comparison of energy cropping with this land use excludes the energy crop subsidy and is based on the maintenance costs for set-aside land [7]. Gross margins in the NFS include labour costs, but not land rental or fixed farm costs. These costs are therefore not considered in the economic analyses of energy crops applied here, following the examples of [14,16,17]. The use of contractor prices for specialised operations such as planting and harvesting ensures that specialised machinery costs are indirectly accounted for.

In early 2007, the Irish Department for Agriculture and Food announced planting subsidies for SRCW and *Miscanthus*, to cover up to half of the establishment costs [19]. Planting on up to 1400 hectares is to be funded in 2007, and will be accompanied by an €80 $ha^{-1} a^{-1}$ energy-crop premium top-up (bringing the total energy-crop premium to €125 $ha^{-1} a^{-1}$, except on set aside). The combined impact of these supports on discounted annual gross margins is included in NPV model runs for *Miscanthus* and SRCW, and the results presented alongside biomass-price sensitivity.

3. Results

3.1. *Production costs for different supply routes*

Fig. 3a displays the total, discounted annual production costs for each hectare of SRCW and *Miscanthus*, up to the farm gate, over plantation lifetimes of 23 and 16 years, respectively. Fig. 3b displays the same costs expressed per t DM product. In both instances, total production costs for each supply route are broken down into major source categories. Discounted, annualised production costs for *Miscanthus* range from €430 to €559 ha^{-1}, or, expressed per unit product, from €37 to €48 t^{-1} DM. These compare with annualised SRCW production costs ranging from €275 to €407 ha^{-1}, or €31 to €46 t^{-1} DM. For *Miscanthus*, the B (baled) harvest strategy was slightly more expensive than the C (chopped) harvest strategy (discounted costs of €48 compared with €43 t^{-1} DM), whilst the A (contractor) supply strategy (delayed, chopped harvest and immediate supply) was the least expensive at €37 t^{-1} DM. For SRCW production, the C1 (chip and dry) supply strategy was the most expensive, though only slightly more costly than the S1 (stick harvest and chip) supply strategy (discounted cost of €46 t^{-1} DM), and the C2 (wet-chip supply) strategy was the least expensive (discounted cost of €32 t^{-1} DM).

For SRCW supply strategies, establishment accounted for the largest portion of production costs (€13 t^{-1} DM), whilst annual harvesting accounted for the largest portion of

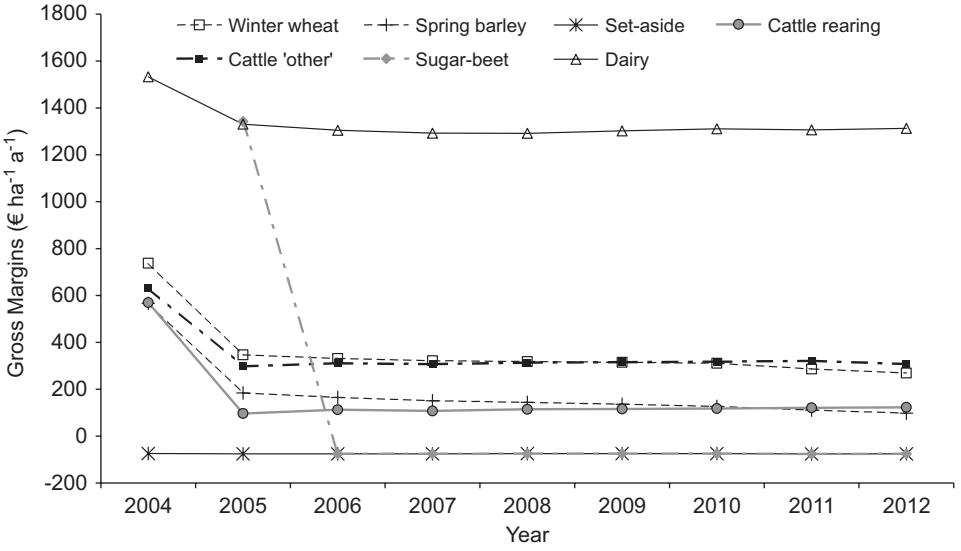

Fig. 2 – FAPRI-Ireland farm-level forecast gross margins for conventional systems, and the range of discounted annualised gross margins for energy crops for reference.

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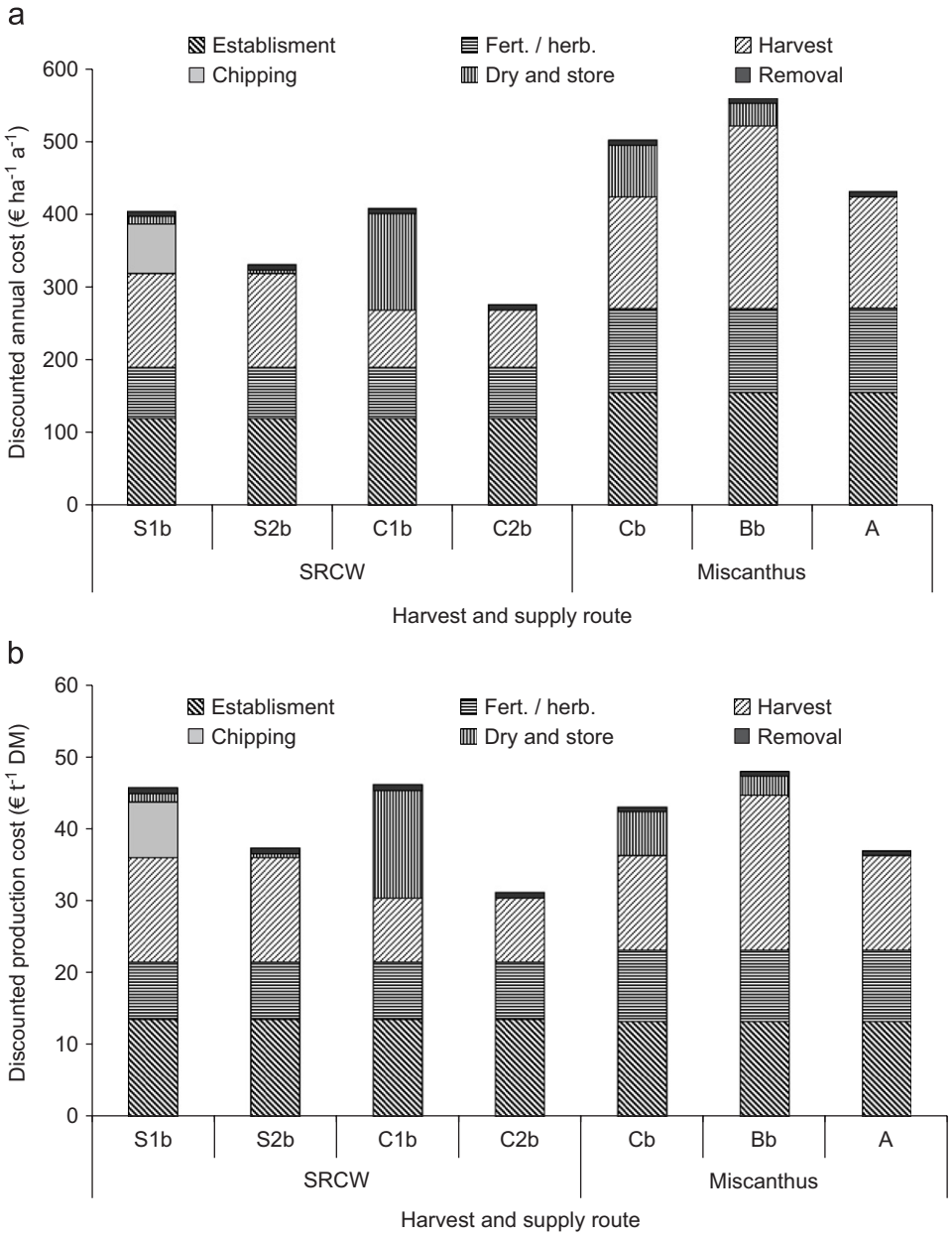

Fig. 3 – 2006 production costs, expressed per hectare (a) and per tonne of combustible dry matter (b) for SRCW and *Miscanthus* broken down into main source categories.

Miscanthus production costs. Drying and storage incurred the largest cost in the case of the SRCW C1 supply strategy (€15 t^{-1} DM), though incurred low costs for the other supply strategies. Fertiliser and herbicide application costs were significant, accounting for approximately one fifth of SRCW production costs (€8 t^{-1} DM) and approximately one quarter of *Miscanthus* production costs (€10 t^{-1} DM). After discounting and division over the crop lifetime, the cost of crop removal made a small contribution to overall costs.

3.2. *Energy crop gross margins and sensitivity analyses*

Table 5 displays annualised discounted profit margins for SRCW and *Miscanthus*, and variation of these margins in response to changed costs, yields and discount rates. Values are centred around mid-costs (Table 3), mid-yields (Table 4), a 5% discount rate, and a biomass price of €100 t^{-1} DM (adjusted to 95 and 87 € t^{-1} DM for SRCW S2 and C2 strategies). These values vary according to low and high estimates for costs, presented in Table 3, yields presented in Table 4, and alternative discount rates of 3% and 8%. Based on the mid-cost and mid-price estimates for energy crop production and sale, discounted, annualised gross margins from SRCW range from €211 $ha^{-1}a^{-1}$ for the C1 supply strategy to €270 $ha^{-1}a^{-1}$ for the C2 supply strategy (Table 5). For *Miscanthus*, gross margins are €383 and €326 $ha^{-1}a^{-1}$ for chopped and baled supply strategies, respectively (Table 5), and €172 $ha^{-1}a^{-1}$ in the instance of €63 t^{-1} DM Quinn's price.

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Table 5 – Results of sensitivity analyses, comparing discounted, annualised profit margins (2006 prices) at different cost levels, yields and discount rates

	SRCW (€ ha^{-1} a^{-1})				*Miscanthus* (€ ha^{-1} a^{-1})	
	S1	S2	C1	C2	C	B
Cost						
Low	373	364	385	397	586	519
Mid	245	261	211	270	383	326
High	−139	−71	59	166	103	−13
Yield						
Low	32	44	19	49	270	230
Mid	245	261	211	270	383	326
High	296	314	257	324	609	535
Discount rate						
3%	294	314	251	325	472	405
5%	245	261	211	270	383	326
8%	128	139	102	146	279	232

Mid yield and cost estimates, 5% discount rate, and €100 t^{-1} DM price is applied unless otherwise stated.

Applying the low cost estimates results in substantially higher discounted annual gross margins, of up to €397 and €586 ha^{-1} a^{-1} for SRCW (C2a) and *Miscanthus* (Ca), respectively. Conversely, applying the high cost estimates diminishes discounted annual gross margins, down to −€139 and −€13 ha^{-1} a^{-1} for SRCW (S1c) and *Miscanthus* (Bc), respectively. Positive gross margins were maintained assuming combustible yield reductions of 50% and 30% for SRCW and *Miscanthus*, but were reduced by up to 91% (SRCW-C1) and 30% (*Miscanthus*-C), respectively (Table 5). The assumption of yield increases of 17% and 30% for SRCW and *Miscanthus* resulted in gross margin increases of up to 22% (SRCW-C1) and 64% (*Miscanthus*-B), respectively (Table 5). Discounted *Miscanthus* gross margins exceeded €600 ha^{-1} a^{-1} under the high-yield scenario. Gross margins proved less sensitive to variation in discount rates than to variation in costs and yields. Reducing the discount rate applied from 5% to 3% increased discounted annual per hectare gross margins to between €251 (39% increase) and €325 (20% increase) for SRCW, and to €405 (24% increase) and €472 (18% increase) for *Miscanthus*. Increasing the discount rate applied from 5% to 8% reduced discounted annual per hectare gross margins to between €102 (43% decrease) and €146 (46% decrease) for SRCW, and to €232 (29% decrease) and €279 (27% decrease) for *Miscanthus* (Table 5).

Discounted annual gross margins were highly sensitive to variation in the energy crop biomass price from 70 to 130 € t^{-1} DM (Table 6). At a €70 t^{-1} DM price, SRCW gross margins were reduced to between 33 and 110 € ha^{-1} a^{-1}, and *Miscanthus* gross margins to 109 and 167 € ha^{-1} a^{-1}. At a €130 t^{-1} DM price, SRCW gross margins were increased to between 388 and 436 € ha^{-1} a^{-1}, and *Miscanthus* gross margins to 651 and 708 € ha^{-1} a^{-1}. Incorporating the new 50% establishment grant (up to €1450 ha^{-1}) and €80 ha^{-1} a^{-1} energy-crop premium top-up would result in substantial increases for energy-crop gross margins. The impact is especially great for low farm-gate biomass prices, where gross-margins are increased by between 105% and 352% for SRCW, and by between 87% and 132% for *Miscanthus*. At mid- and high-biomass prices, these subsidies would have a proportionately smaller, but significant, overall effect on discounted annual gross margins. For example, they would increase mid-price gross margins for SRCW by between 43% and 55%, and for *Miscanthus* by 38% and 44%, enabling healthy mid-price discounted gross margins of up to 386 and 527 € ha^{-1} a^{-1} for SRCW and *Miscanthus*, respectively (Table 6).

3.3. *Waste-water treatment*

There is an increasing realisation of the potential to utilise SRCW for biofiltration treatment of wastes and contaminated land, owing to the dense root network and high transpiration rate of willow. Bjorsson [36], and Rosenqvist and Dawson [18], estimated the waste-water treatment capacity of SRCW and attributed values to this, in the contexts of Sweden and Northern Ireland respectively. Figures from [18] were applied here, with the assumption that circumstances should be similar between the North and Republic of Ireland. Their figures comprised an estimated annual cost of €1306 ha^{-1} for capital investment in irrigation ponds, pumps, pipes, pumping costs, labour, etc., and a 100% reduction in fertiliser costs. The potential net annual income from waste-water treatment, assuming full payment of the conventional treatment cost, was estimated at between €1159 and €2947 ha^{-1} depending on conventional treatment method. Here, the mid-point value of €2053 ha^{-1} a^{-1} was used as an estimate of farm revenue from WW treatment, resulting in a net income of €747 ha^{-1} a^{-1}, before discounting. Table 6 displays discounted, annualised gross margins for the range of energy-crop biomass price scenarios, for mid-yield estimates, when WW treatment returns are applied. Assuming a biomass price of €100 t^{-1} DM, WW treatment could raise gross margins substantially to between €774 and €833 per hectare per year for SRCW.

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Table 6 – The impact of varying farm-gate energy crop biomass prices (70, 100 and 130 € t^{-1} DM), use of SRCW for waste-water treatment, and recently announced 50% establishment subsidy with €80 $ha^{-1}a^{-1}$ top-up payment, on discounted, annualised gross margins for different energy crop strategies

Price (€ t^{-1} DM)	SRCW (€ $ha^{-1}a^{-1}$)				*Miscanthus* (€ $ha^{-1}a^{-1}$)	
	S1	S2	C1	C2	C	B
Biomass						
70	68	84	33	110	167	109
100	245	261	211	270	383	326
130	423	439	388	436	708	651
Biomass+WW treatment						
70	631	647	596	673		
100	808	824	774	833		
130	986	1002	951	999		
Subsidy (50% est.+€80 a^{-1})						
70	184	200	149	226	311	254
100	362	377	327	386	527	470
130	539	555	504	552	853	795

3.4. *Comparison with conventional agricultural crops*

Fig. 2 displays the data from the farm-level FAPRI projections for selected conventional agricultural systems, extrapolated from 2004 data, and running until 2012. Most of the conventional agricultural systems exhibit a sharp decline in gross margins between 2004 and 2005, after which they remain relatively stable through to 2012, reflecting the decoupling of subsidy payments from production (and thus exclusion from gross margin calculations) in 2005. Sugar-beet gross margins decline steeply from a high 2005 value of €1342 $ha^{-1}a^{-1}$ to the equivalent of set-side payments in 2006, reflecting the recent announcement that the only sugar processing factory in Ireland is to close. On the other hand, high initial dairy gross margins remain fairly steady at over €1300 $ha^{-1}a^{-1}$ through to 2012.

Fig. 4 compares annualised, discounted (mid-estimate) gross margins for the different conventional agricultural land uses and energy cropping strategies, calculated over the 16 and 23 year timescales of *Miscanthus* and SRCW cultivation, respectively. Both the *Miscanthus* C and B supply strategies prove highly competitive with all but the dairy (€965 $ha^{-1}a^{-1}$) land uses, whilst the *Miscanthus* A strategy fails to match the gross margins for 'cattle and other' (€229 $ha^{-1}a^{-1}$) or winter wheat (€214 $ha^{-1}a^{-1}$) land use classifications, but is competitive with spring barley (€87 $ha^{-1}a^{-1}$), sugar beet (−€56 $ha^{-1}a^{-1}$), set aside (−€56 $ha^{-1}a^{-1}$) and cattle rearing (€88 $ha^{-1}a^{-1}$). All but the C1 SRCW strategies proved competitive with all the land use classifications except dairy (€867 $ha^{-1}a^{-1}$). Removing the €45 $ha^{-1}a^{-1}$ subsidy has a small impact on energy crop returns, reducing discounted gross margins for *Miscanthus* by approximately €35 $ha^{-1}a^{-1}$, and for SRCW by approximately €31 $ha^{-1}a^{-1}$. Therefore, all energy crop production and supply strategies return gross margins considerably higher than set aside (Fig. 4). The annualised, discounted gross margin resulting from including WW treatment in combination with the mid-range SRCW-S1 strategy (€808 $ha^{-1}a^{-1}$) proved highly competitive with all land uses, and was only 10% below the average dairy gross margin. Similarly, including the recently-announced energy-crop establishment grant and subsidies significantly elevated energy-crop gross margins compared with most conventional land uses (Fig. 4). This was especially true for the SRCW C2, wet-chip supply strategy, reflecting the lower overheads for this strategy (Fig. 3). For simplicity, these comparisons were made for mid-estimate energy-crop gross margins only. Varying the yield, biomass price and activity-cost estimates (Tables 5 and 6) would substantially alter these comparisons.

4. Discussion

4.1. *Energy crop production costs*

The least certain cost estimates are those for storage and drying. These largely depend on the techniques used, but the range of values in the literature also reflects different methods of calculation. If the shed storage cost of €2.77 t^{-1} DM $month^{-1}$ calculated in [26] was applied in this study, wood chip production would increase in cost by approximately €284 $ha^{-1}a^{-1}$ (assuming 9.5 months average storage). Such fixed costs are not directly considered in the FAPRI-Ireland model projections, or energy crop cost calculations in this study, although machinery costs are indirectly accounted for through contractor costs for planting, maintenance and harvest operations. Flexible harvest timing for SRCW offers the possibility to plan harvesting around storage availability, and [14] ignored fixed costs associated with SRCW production on the assumption that only 10–15% of any farm's land would be converted to SRCW cropping, ensuring that existing facilities would be adequate. For stick-harvested SRCW, and *Miscanthus*, 6 months of outside storage may reduce moisture content to less than 15% [30,37]. In this study, a final moisture content of 20% or less was assumed after

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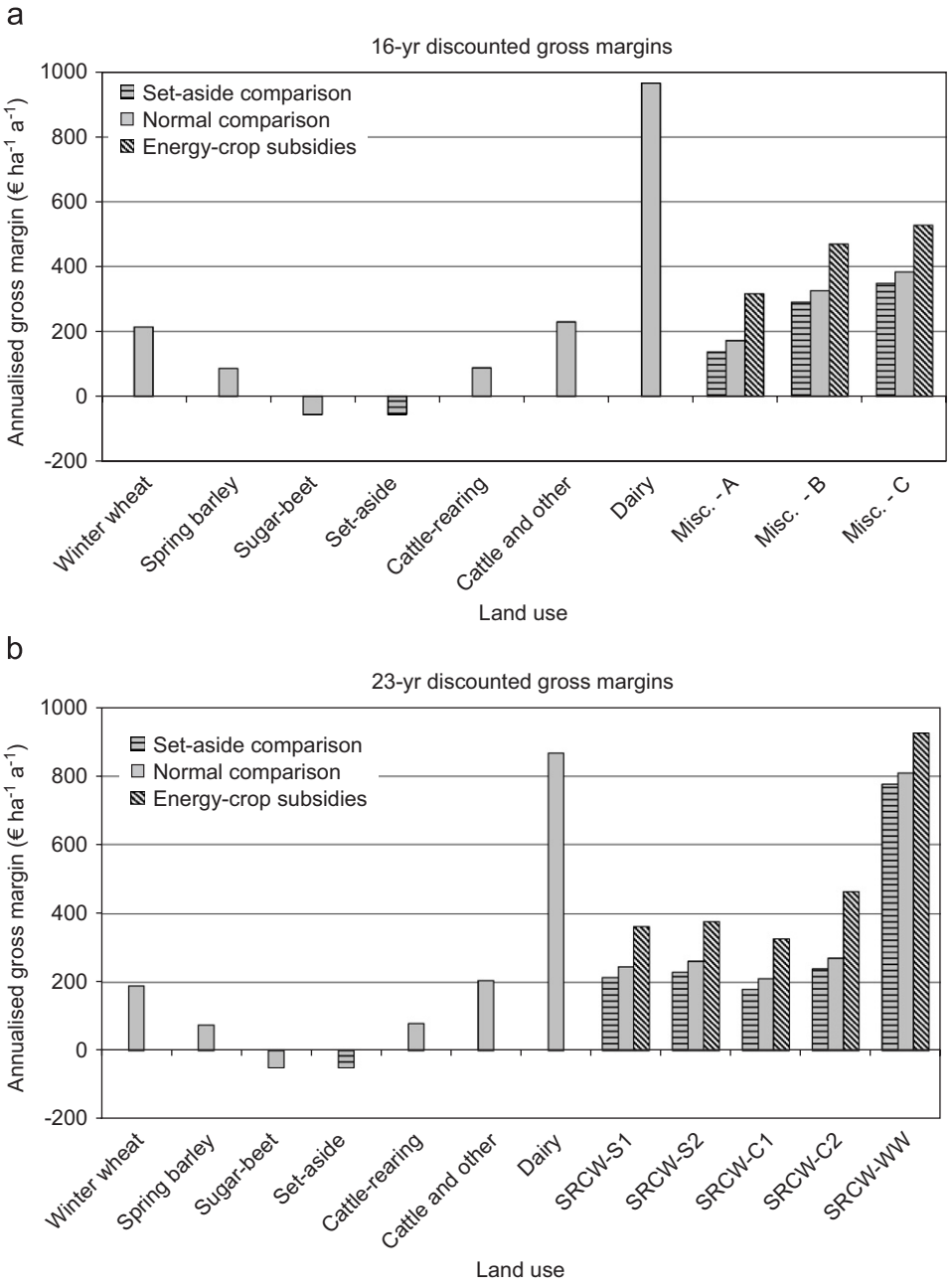

Fig. 4 – Discounted, annualised gross margins for conventional agricultural systems and energy crop plantations over the 16 (a) and 23 (b) year plantation lifetimes of *Miscanthus* and SRCW. Comparisons with set aside (minus €45 ha^{-1} a^{-1} energy crop subsidy), without, and with, additional subsidies, respectively.

outdoor storage under plastic sheeting, at relatively low costs (Table 3). Harvesting SRCW as chips requires the forced drying of wood chips prior to storage, unless moist chips are to be used immediately (e.g. in gasification boilers or large combustion plants) or cheaply dried by the consumer (e.g. using waste process-heat). Forced ventilation drying of wood chips with heated air is expensive, and was calculated to cost between €14 and €29 t^{-1} DM by [38]. Rabbit fencing was not accounted for in the 'mid-cost' estimates, though this cost will only be incurred if there are significant rabbit populations in the area, and will ultimately be highly dependent on the size of the plot. Increasing establishment costs by €500 ha^{-1} to account for rabbit fencing would result in discounted, annualised gross margins decreasing by approximately €22 ha^{-1} a^{-1} (<10%).

Higher costs of production per hectare for *Miscanthus* compared with SRCW reflect the higher fertiliser requirements, annual (compared with 3-yearly) harvesting requirement, and shorter plantation time over which establishment costs are divided for *Miscanthus*. However, these higher costs are compensated for by higher yields, and discounted production costs per tonne of DM (Fig. 2) are similar for SRCW (€32–€47) and *Miscanthus* (€36–€47). In fact, non-discounted, price-inflated costs per tonne of DM are

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higher for SRCW (€56–€83 t^{-1} DM) than for *Miscanthus* (€52–€67 t^{-1} DM), reflecting the longer discount and price-inflation period used in SRCW calculations (23 compared with 16 years). Sensitivity analyses indicated that the cost of SRCW production was more susceptible to variation in yield and discount rate than *Miscanthus*, reflecting the higher portion of costs (fertiliser application, annual harvest and storage) linked directly with yield, and the shorter crop lifetime, in the instance of *Miscanthus*. The cost of dried wood chip production quoted by [39] (€50 t^{-1} DM) lies between the discounted and non-discounted price-inflated costs of dried wood chip production calculated here.

4.2. *Supply strategies*

It is apparent that the harvest and supply strategy has a critical impact on production costs, and on additional transport, handling and preparation costs that may be borne by either the producer or consumer. Combined harvest and chipping is cheaper than stick harvest (€417 compared with €682 ha^{-1}), and saves substantial post-harvest chipping costs of €226 ha^{-1} (decentralised), or €106 (centralised), for the *farmer*. If SRCW is to be used as a feed stock for peat power stations, adequate size-reduction may be achieved through chunking, rather than chipping, with decentralised costs of €86 ha^{-1} (based on [26]). Unless chips are immediately used, they incur substantial drying costs of €701 ha^{-1} [26] and will require shed storage space, compared with cheap outdoor stick storage. The lower density of *Miscanthus* enables natural drying of both baled[3] and chopped material [30]. Higher costs for baled harvest compared with chopped harvest (€389 vs €287 ha^{-1}) are partially offset by lower storage costs for baled material (€48 vs 110 ha^{-1}), and may also result in higher combustible yields through collection of senesced leaf material (though this would also increase nutrient uptake and deteriorate combustion properties). Transport of the baled material may also be cheaper, though this should be considered against any necessary disaggregation and chopping costs incurred prior to combustion. Non-adjusted transport and handling costs calculated by [27] of 6.8 and 8.9 € t^{-1} over 20 km for baled and chopped *Miscanthus*, respectively, are considerably higher than biomass transport costs of €4.1 t^{-1} for 50 km calculated for Ireland by [5]. Such costs are difficult to accurately quantify in the absence of national case-studies.

Here, variable costs incurred by the consumer according to the supply strategy are reflected in variable biomass prices: i.e. the chipping costs for supply of stick bundles, and the additional transport costs and reduced LHV of wet wood chips, are translated into reduced biomass prices received for these products. This standardises the product output to an equivalent of chipped, dried (maximum 20% MC) wood chips for SRCW, but has the effect of reducing the impact of supply-strategy on gross margins for farmers. If additional processing costs were borne by the consumer, farmers could realise substantially higher profits. For example, applying the standard farm-gate price of €100 t^{-1} DM to wet wood chip in the NPV model (instead of the adjusted €87 t^{-1} DM), results in the C2 production strategy realising discounted gross margins of €347 (rather than €270) ha^{-1} a^{-1}. Ultimately, there will be a need for coordination along the supply–consumer chain, and this may optimise cost-sharing between producers and consumers. For example, some large consumers may be able to cost-effectively dry wood chip utilising waste heat (with associated energy-balance benefits compared with forced drying). The lowest-cost supply strategy depends on a number of factors, including moisture content at harvest, the time between harvest and combustion, the method of energy conversion, the possibility to utilise waste heat in drying [26]. Further work is needed to explore the logistics and feasibility of possible energy-cop supply to consumer chains within Ireland, with the aim of optimising the energy balance and economics. The farm-gate biomass prices applied in this paper, for chipped/chopped biomass at 20% moisture content, are used as the input to energy-crop electricity and heat production in a related paper [12].

4.3. *Prices and market establishment*

The farm-gate price range of 70, 100 and 130 € t^{-1} DM applied here for indicative purposes is based around current actual prices in Ireland's fledgling wood-fuel market. In N. Ireland, Rural Generation is delivering wood chips for around €100 t^{-1} DM [39], and wood pellets are sold for prices of €168 t^{-1} DM in bulk, and up to €333 t^{-1} DM by the bag [31]. Pellets will command significantly higher prices than wood chips due to their higher energy content (20.0 GJ t^{-1} DM compared with 18.1 GJ t^{-1} DM) and superior handling and combustion properties. Irish wood chip prices are high compared with some wood chip price estimates used elsewhere, such as the €40 and €59 t^{-1} DM[4] used by [16] to calculate the economics of willow production in Poland. However, those same authors refer to a wide range of wood chip prices in Europe, citing examples ranging from €47 t^{-1} DM[4] in Germany to €94 t^{-1} DM[4] in Denmark. *Miscanthus* prices are more speculative, as no market exists for *Miscanthus* yet in Ireland. It is assumed that ultimately energy producers may be willing to pay the same price for *Miscanthus* as for wood chip once a market is established, but initially farmers can only expect the farm-gate price of €63 t^{-1} DM offered by the contractors (although presumably this is less than the end consumer is willing to pay). Whilst farmers could maximise farm-gate prices through direct supply to final consumers, intermediaries may prove necessary to hedge some of the risk involved and guarantee contracts for both farmers and consumers. Additionally, as indicated by [17], initial small-scale 'pioneer grower' costs could prove to be higher than cost estimates used here as techniques are adapted to, though this effect could be reduced if contractors are used. It is therefore possible that initial returns for pioneer farmers may be closer to those based on the lower price estimate of €70 t^{-1} DM.

There are signs that momentum is building in the Irish biomass-fuel market, with positive implications for future

[3] Assuming moisture reduction prior to late winter harvest.

[4] Converted from 2003 price expressed per MWh fuel to 2006 price expressed per t DM, based on 5 MWh (18 GJ) t^{-1} DM lower heating value and inflation values in Fig. 1.

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energy-crop biomass prices. In recent years, a small number of wood chip suppliers have begun operating in Ireland, and the relatively new Edenderry peat power-station[5] has recently been taken over by Ireland's peat supply board (Board nà Mona) with the intention of experimentation with alternative biomass fuels. After adding transport costs and tax to the farm-gate prices used in this study, *Miscanthus* and SRCW were calculated to be borderline competitive as fuel for electricity generation compared with peat through co-firing, and highly competitive as a source of heat generation in domestic boilers (even at a farm-gate price of €130 t^{-1} DM) [12]. Upward pressure on energy prices through fossil fuel and CO_2 emission costs may result in large-scale energy producers willing to pay more for biomass fuels in the future, towards the speculative upper price level of €130 t^{-1} DM used here. Rosenqvist and Dawson [17] report that market development in Sweden resulted in a decline in wood chip prices to around €57 t^{-1} DM (~2003) as a consequence of abundant supply from vast forests and large areas of efficient SRCW cultivation. The availability of competing wood sources in Ireland is far lower than in Sweden, with less than 10% of Ireland's national land area forested, compared with 70% under agricultural uses. Utilisation of alternative biomass supplies, such as meat and bonemeal and forestry thinnings, is likely in Ireland, though whether this dampens or primes the market for energy-crop biomass will depend on the scale of future demand for biomass.

The recently announced establishment and annual subsidy top-up payments for *Miscanthus* and SRCW cultivation in Ireland [19] significantly improve NPV calculations for energy-crop plantations, and extend the benefit of energy crops compared with most of the conventional agricultural systems referred to in this study. These payments offer good insurance against gross revenues being diminished by high costs and low yields, and generate a high probability that energy-crop gross margins will be favourable compared with alternative land uses. However, the greatest impact is likely to be the reduced risk and shorter payback period associated with the 50% establishment grant (two-thirds paid in the establishment year, one third in the subsequent year). Worth up to €1450 ha^{-1}, this grant substantially reduces the high initial outlay (2736 and 2470 € ha^{-1} for SRCW and *Miscanthus*, respectively) required from farmers to cultivate these energy crops, and thus reduces the risk-based inertia and payback commitment period.

4.4. *Competitiveness with conventional crops*

The decoupling of subsidy payments from production in January 2005 substantially decreased gross margins attributable to conventional agricultural production, although dairy gross margins remain relatively high. The proposed reform of the EU common market organisation for sugar, and the decision by Irish Sugar to cease processing sugar in 2006, reduces the market based gross margin for sugar beet to levels equivalent to that of set-side land. In combination with the modest EU biofuel subsidy of €45 ha^{-1} a^{-1}, and recently announced Irish-specific subsidies (for a restricted number of farmers), these factors present a strong opportunity for energy crops, such as *Miscanthus* and SRCW, to compete financially with existing agricultural land uses. When all possible land uses are compared as a stream of future net revenue over the plantation lifetimes of *Miscanthus* and SRCW using the NPV method, annualised returns for these crops prove to be highly competitive with a number of the major current agricultural land uses. In particular, future gross margins predicted for sugar beet, spring barley and cattle rearing are low, and uncompetitive with any of the energy cropping strategies considered here. The most profitable energy-cropping strategies (i.e. SRCW-C2 and *Miscanthus* C) are competitive with all the other land uses considered, except dairy. Well-managed, and planted on good-quality soils, the high DM yields attainable from these energy crops offer relatively high earning potential for farmers compared with current options. Planting on set-aside land is financially an attractive option, but would disrupt current crop rotation systems and may cause some logistical difficulties. Opportunities for multiple uses, such as WW and sewage sludge treatment, further enhance the financial attractiveness of SRCW, and could substantially increase farm revenues.

In addition to biomass price assumptions discussed earlier, calculated returns from energy crops were based on mid-yield and mid-cost estimates, and a discount rate of 5%. Low yields could render SRCW uncompetitive with average gross margins for productive agricultural land uses, although *Miscanthus* remains competitive due to lower yield-related costs (Table 5). If these low yields are caused by poor growing conditions, presumably conventional agricultural productivity would also be impaired, and comparative gross margins would be lower. This may prove to be an advantage for SRCW, which does comparatively well in wet conditions [40]. The greatest potential threat to energy crop gross margins is variation in cultivation costs. The high-cost estimates used in the sensitivity analyses applied here result in negative returns for some energy crop harvest and supply strategies (Table 5). These are highly pessimistic estimates, however, incorporating the highest costs found in the literature for all activities, and include high fixed costs not included in the compared conventional land use gross margins. With respect to the impact of biomass pricing, even at the lower biomass price of €70 t^{-1} DM, returns would be competitive with cattle rearing and spring barley, not to mention set aside and sugar beet. Generally, the annual harvest and higher proportion of yield-related costs make *Miscanthus* less susceptible to variations in the parameters applied to the economic model.

4.5. *Barriers and opportunities*

The main barriers to realising potential energy crop profits are market uncertainty combined with the risk of large upfront establishment costs. Farmers are reluctant to invest into such

[5] A modern circulating fluidised bed boiler design capable of co-firing high proportions of biomass alongside peat with no major modifications. Two similar power stations have recently commenced electricity generation, bringing total peat power station capacity to 375 MW_e.

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long-term financial commitments as SRCW and *Miscanthus* plantations before a developed market for biomass emerges. Conversely, potential consumers (householders, building managers, electricity generators) are reluctant to invest in the technology necessary for energy crop utilisation before guaranteed biomass supplies become established. These supplies may initially be dominated by non-energy-crop biomass. There are positive signs of change, in the form of the recently announced *Miscanthus* and SRCW establishment subsidies, and significant consumer subsidies for wood heat (up to €4200 to householders investing in wood boilers and stoves). However, the ongoing challenge will be to coordinate planning of supply strategies between potential consumers and farmers, and to integrate policy between relevant government departments. As indicated elsewhere (e.g. [26]), it is clear that overall supply-chain costs could be reduced through coordinated, logistical planning of supply and utilisation networks.

The higher yields, higher potential profits, shorter period to first harvest, greater similarity with existing cropping practices, and the potential to apply existing farm machinery and techniques, may favour *Miscanthus* over SRCW from a farmer perspective. However, SRCW may be grown on wetter, less agriculturally productive (less profitable) soils, and offers the opportunity to generate extra revenue through WW treatment. Wood chip is also a more suitable fuel than *Miscanthus* for small-scale heating boilers (*Miscanthus* would need to be pelleted, with associated logistical and financial complications). Initial *Miscanthus* utilisation is most likely to occur via co-firing in peat power stations, but broader utilisation could be achieved through research and development into utilisation in smaller boilers (e.g. assessing the feasibility of pelleting), or following gasification or lignocellulosic digestion to produce gaseous/liquid fuels. Further research and development could identify optimum utilisation strategies, in terms of supply chains and inter-sectoral sustainable development policy. For example, if it was decided to use *Miscanthus* as the sole feed stock to achieve the policy target of 30% biomass co-firing in peat power stations, then 34,000 ha of land would need to be planted with *Miscanthus*, with a 3-year delay until peak yields are attained. The extent, and level, of government financial support for farmers will need to be carefully considered and targeted. The recently announced subsidies, directed towards 1400 ha in the first year, may be regarded as an informative pilot scheme.

Ultimately, the comparisons here were based on many assumptions, and used average values. Gross margins within Ireland vary widely according to variations in climate and soil type [41], and management practices on individual farms. Thus, the decision as to whether energy crops are an attractive alternative will vary among farms, and according to the views of individual farmers. However, data presented here indicate that SRCW and *Miscanthus* are promising substitutes to conventional land uses in an emerging era of area-based agricultural subsidy payments and higher energy prices. Future extension of the EU ETS may add further financial incentives for farmers to cultivate *Miscanthus* and SRCW, which have relatively low cultivation emissions and could enhance soil C sequestration [4].

5. Conclusions

On a per hectare basis, *Miscanthus* cultivation is more expensive than SRCW cultivation, owing to higher fertiliser requirements, annual harvest and a shorter lifetime over which establishment costs are absorbed. However, *Miscanthus* is anticipated to produce higher DM yields than SRCW, resulting in similar production costs per tonne DM. Conservative peak combustible yield estimates (after harvest and storage losses) of 14 and 10 t^{-1} DM ha^{-1} a^{-1} were applied to *Miscanthus* and SRCW economic analyses. Crop storage and drying are associated with the greatest uncertainty, and the choice of supply strategy results in variation of these and post-production transport, handling and combustion costs. For SRCW, producing wet wood chip for immediate sale is the most profitable supply strategy, even after prices were adjusted to reflect additional transport costs and reduced LHV compared with dried wood chip. These costs, borne by the consumer, may be mitigated if wood chip is used close to where it is produced, and if process heat can be used for drying (requires coordinated supply chain). Consequently, farmers may not need to reduce the farm-gate prices for wet wood chip supply, enabling higher revenues to be realised. Stick-harvest and outdoor drying may be the most realistic strategy, both from a whole-chain cost and energy-use perspective. For *Miscanthus*, chopped harvest is the cheaper supply strategy when compared with baling, but it may be associated with higher handling costs beyond the farm gate.

Profitability was highly dependent on production costs, and annualised gross margins became negative for some supply strategies when the highest cost estimates were applied. However, profitability was maintained, albeit diminished, when low yields were assumed, owing to the assumed proportionality of many costs to harvestable yield. Variations in the discount rate had a modest, but not critical, impact on discounted gross margins. Gross margins were critically dependent on the farm-gate price of biomass, though remained positive at the low end of the 70, 100 and 130 € t^{-1} DM range applied to both *Miscanthus* and SRCW. The mid price of €100 t^{-1} DM is indicative of current circumstances in Ireland for wood chip, but is more speculative for *Miscanthus*, for which no real market yet exists. Predicted gross margins based on the market establishment efforts of one company are modest, and probably low compared with longer-term potential considering likely future demand for 'C-neutral' biomass fuels.

Compared with gross margins accruing from conventional agricultural land uses, many of which exhibited a marked decline in 2005 after subsidies were decoupled from production, energy crop gross margins predicted here are highly competitive. In particular, average cattle rearing, sugar beet and spring barley systems are forecast to return low or negative gross margins against which discounted energy crop returns of €211–383 ha^{-1} a^{-1} are highly attractive. In addition, although not activating the EU biofuel production subsidy, energy crops grown on set-aside land do activate the set-aside subsidy, and generate a strong financial incentive for cultivation compared with the alternative cost burden of set-aside maintenance. The recently announced government subsidy

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scheme for *Miscanthus* and SRCW improves the likely returns from these crops, and, more importantly, considerably reduces the investment risk. However, the establishment of an energy-crop biomass market will require significantly higher establishment rates than envisaged under this new scheme.

In conclusion, the main barriers to energy crop production are the high upfront establishment costs in combination with long payback periods, lack of an established biomass market in Ireland associated with future price uncertainties, and a lack of policy coordination among sectors. Dissemination to farmers of energy crop knowledge and opportunities, and an extension of recently announced establishment subsidies in the context of coordinated policy, could promote a new market for energy-crop biomass in Ireland. Research and development work will be needed to identify optimum supply and utilisation strategies from a national perspective. Potential farmer and consumer financial benefits, combined with significant potential GHG emission reductions, should encourage government support for these crops.

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