Supporting Information

Site Variation in Life Cycle Energy and Carbon Footprints of Mallee Biomass Production in Western Australia

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The Supporting Information contains:

15 Pages

5 Figures

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1. Location of nine sites in Western Australia for this study

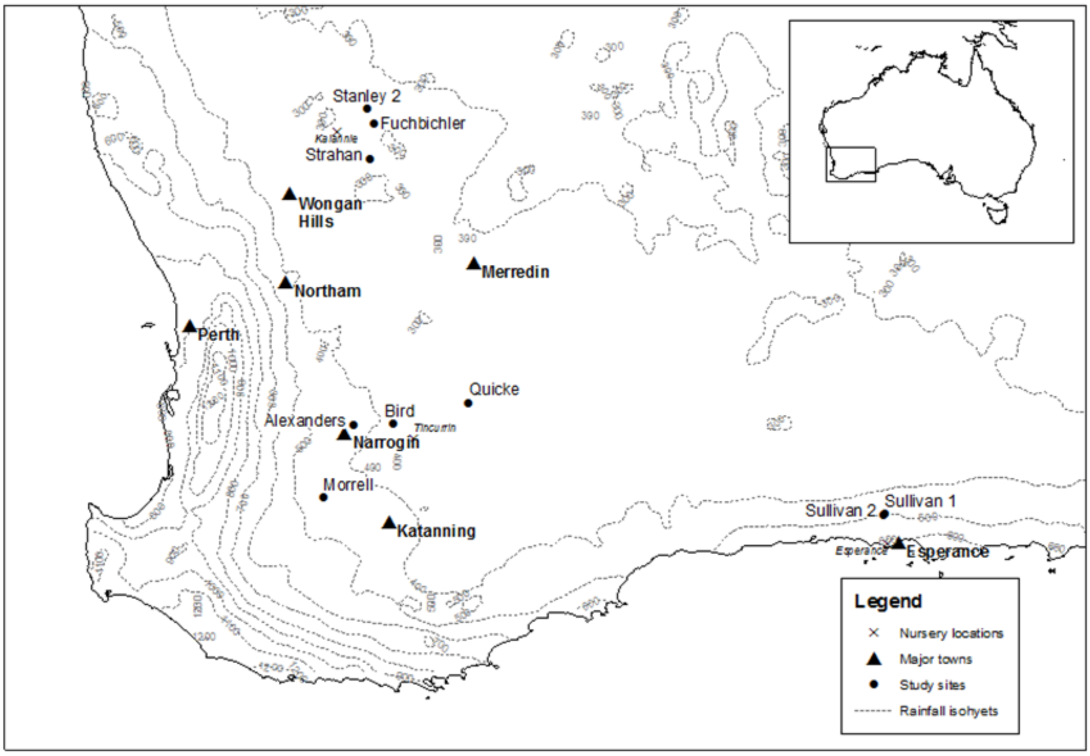


Figure S1. The location of the sites in this study as shown in a map of western Australia.

Table S1. Site location, rainfall (2005-2010), evaporation, mallee species, and year planted for the sites included in this study.

Site	Nearest town-site	Lat	Long	Mean Annual Rainfall 2005-2010 (mm)	Mean Annual Evaporation (mm)	Mallee Species [a]	Planting Year
1	Alexander	-32.87	117.25	374	1653	pb	1996
2	Bird	-32.85	117.59	315	1630	ll	2000
3	Fuchbichler	-30.29	117.43	272	2342	ll	1999
4	Morrell	-33.48	117.00	416	1514	ll	1999
5	Quicke	-32.67	118.24	309	1832	ll	1997
6	Stanley 2	-30.17	117.37	284	2342	pl	1994
7	Strahan	-30.60	117.39	263	2093	ll	1999
8	Sullivan 1	-33.62	121.78	568	1732	pb	2001
9	Sullivan 2	-33.63	121.76	568	1732	pb	2001

[a] pb: *E. polybractea*; ll: *E. loxophleba* subsp. *Lissophloia*; pl: *E. kochii* subsp. *Plenissima*

2. Approach for Assessing Life Cycle Energy and Carbon Footprints

The goal of this life cycle assessment (LCA) is to quantify the energy and carbon footprints of mallee biomass from nine sites (i.e., Alexander, Bird, Fuchbichler, Morrell, Quicke, Stanley, Stranhan, Sullivan 1, Sullivan 2) across the wheatbelt areas of western Australia (WA), following the ISO 14040 series guidelines.[1] As shown in Figure S2, the overall system consists of biomass establishment (including seed, seedling, planning, site preparation, planting, and post-planting), management (post-harvest), harvest, and on-farm haulage to the farm gate. It should be noted that biomass transport from farm to processing plant is dependent on the road transport distance hence is not included in this study. Therefore, the LCA energy and carbon footprints of mallee biomass in this study are from cradle to farm-gate. The function units of energy and carbon footprints are MJ per dry tonne biomass and kg carbon dioxide equivalent (CO_2-e) per dry tonne biomass, respectively. For the carbon footprint analysis, three main greenhouse gases (GHG), e.g., CO_2, CH_4, and N_2O, were considered in terms of the carbon dioxide equivalent, which is corrected by the global warming potential.

The life cycle inventory (LCI) of mallee biomass is listed in Table S2, which comprises all the activities during the establishment stage. The LCA exhaustively accounts for all activities and processes, which may involve direct (use of agricultural machinery and transport equipment, fertilizer application, etc.) or indirect (production of fertilizers and agrochemicals, production of diesel and petrol fuels, manufacture of agricultural machinery and transport equipment, labour, etc.) energy inputs and GHG emissions during the whole process of mallee biomass production. For example, the energy and GHG emissions due to fossil fuel use consider not only direct energy and emissions from vehicles, but also those associated with the fuel's extraction, production, transport, processing, conversion and distribution. The energy and GHG emissions associated with production, packaging, and delivery of fertilizers and agrochemicals are adapted from GREET model,[2] together with those during the manufacture, maintenance, and disposal of the machinery including harvesters, tractors, trucks, cars, etc. Monetary costs such as labour cost are converted to the energy and GHG emission values using the Australian data on the national average energy consumption and GHG emission per unit gross domestic product.[3]

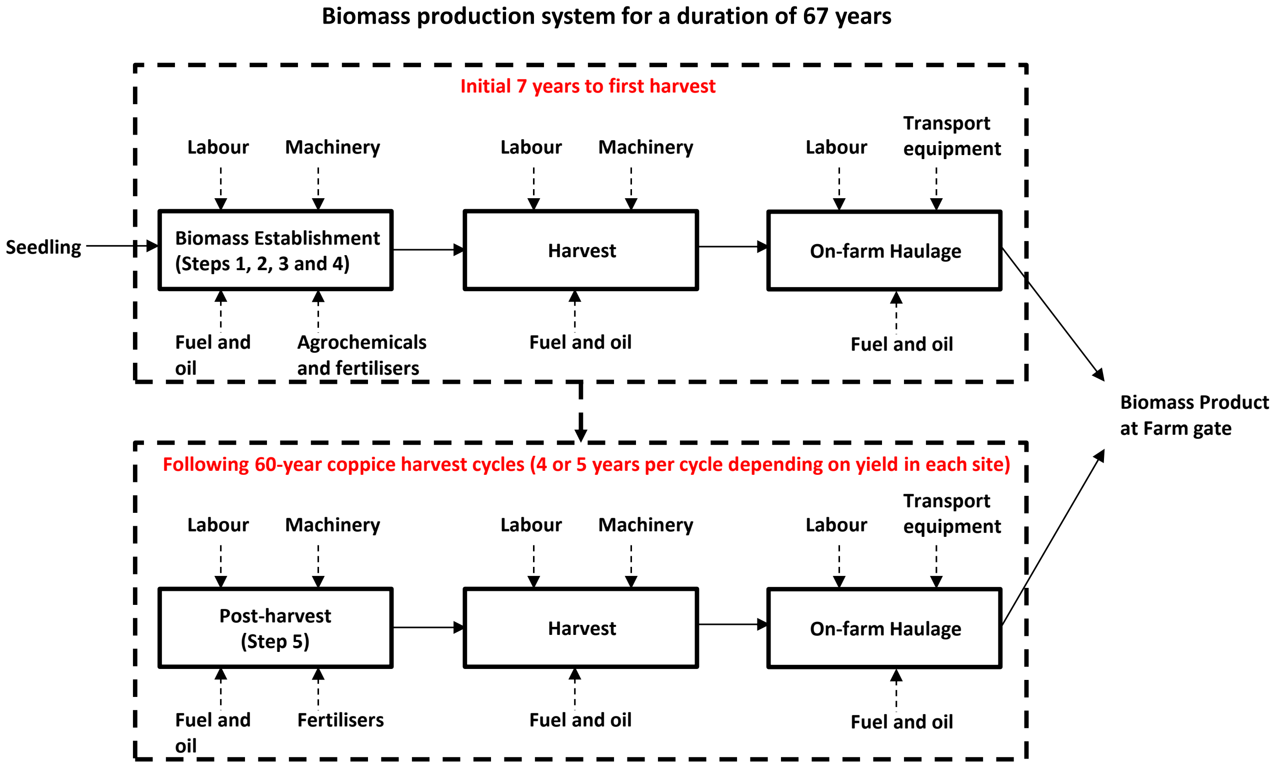


Figure S2. The overall LCA system for mallee biomass production from cradle to farm-gate. The LCA considers the compensation of nutrient export by mallee biomass. Details of Steps 1-5 can be found in Table S2.

The LCA energy inputs and GHG emissions during biomass harvest and on-farm haulage are determined by harvester logistics depending on mallee belt configuration (i.e., 2, 3, and 6 row belt, see Table S3) and harvester performance (i.e., harvester pour rate).[4] For the farm with a low biomass yield, the harvester pour rate can be increased by increasing the harvester speed but the highest speed is limited to 5 km per hour based on the current harvester performance.[5] For the farm with a high biomass yield, the harvester pour rate is limited to 70 kg green tonnes per hour in this study to achieve a reasonably low harvester cost.[6] A harvest logistic model was developed to determine the total required operation hours of harvester and haulout for a typical farm size of 7 ×7 km, considering various biomass yields and mallee belt configurations. The operation hours are then used to estimate the energy inputs and GHG emissions during biomass harvest and on-farm haulage.

The fertilizer application contributes to significant GHG emissions of N_2O and CO_2. In this study, the fertilizer was applied at replacement rates to completely return the extracted nutrients to the soil for sustainable production of mallee biomass. The contents of major nutrients (i.e., N, P, K) in mallee biomass for nine sites are shown in Figure S3.[5] Such data was used to calculate the required fertilizer inputs to completely compensate for the nutrient export in harvested biomass for each site, and the results are shown in Table S3. Detailed emissions for fertilizer application in the field may vary with several factors such as soil type, climate, mallee species and fertilizer application rate.[7] IPCC default method[8] estimates the GHG emissions from several sources, including volatilization of N as NH_3, at a rate of 10% of total N for synthetic N application with 1% conversion to N_2O, direct soil emission of N_2O at 1% for synthetic N application and runoff/leaching to groundwater as nitrate at 30% of total N applied with 0.75% conversion to N_2O. Therefore, the total emission of N_2O is 1.325% of N in synthetic fertilizer. As the N_2O and CO_2 emission data for fertilizer application at various sites are not available, the GHG emissions due to fertilizer application were estimated based on the IPCC Guidelines,[8] considering both direct and indirect N_2O emissions from fertilizer applications.

Land-use change may lead to a variation in soil carbon stock of the land, hence influencing the GHG balance.[9] Depending on the previous land use, the soil carbon stock change can be positive or negative. Unlike our previous study which uses the IPCC Tier 1 approach and a suggested reference carbon stock of 40 t C/ha for wheatbelt land in WA,[10] dynamic change of soil carbon was simulated using the Australian Government's forest carbon accounting model (FullCAM).[11]

The CO_2 sequestrated during mallee biomass production includes not only the above-ground biomass (i.e., wood, bark, twig, and leaf), but also the below-ground biomass (i.e., root). The CO_2 sequestrated by above-ground and below-ground biomass are determined by the carbon contained in each mallee biomass component (i.e., 40% wood, 35% leaf, and 25% bark and twig[12]). The yield of above-ground biomass varies from 3.9 to 15.4 dry tonnes (dt) per hectare per year (see Table S3). Below-ground biomass was simulated by FullCAM model,[11] and a 30% loss of root biomass on harvest was assumed.[13]

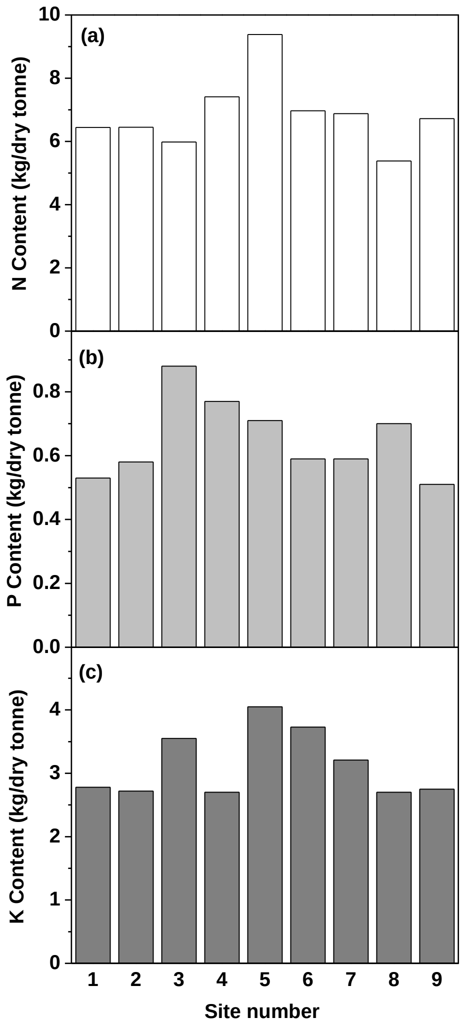


Figure S3. The contents of nutrients in biomass from various sites. (a) N content; (b) P content; and (c) K content. Note: Site 1 - Alexander; Site 2 - Bird; Site 3 - Fuchbichler; Site 4 - Morrell; Site 5 - Quicke; Site 6 - Stanley; Site 7 - Strahan; Site 8 - Sullivan 1; and Site 9 - Sullivan 2.

Table S2. Life cycle inventory of mallee establishment in a typical site of Alexander

Step no.	Operation	Row no.	Job description	Probability of job	Input	Description of input
1	Planning	1	farmer requests advisor to prepare initial plan	100%	advisor office time 2 h + farmer time 1 h	adviser time at $70/h farmer time at $50 h
		2	advisor inspects site to develop field plan, design the job, prepare mapping and order seedlings farmer accompanies on site	100%	travel time 0.75 h + vehicle + distance of 25 km round trip + on-site time 4 h (with farmer) + 6 h office time by advisor	3.0 L 126 kW turbo diesel 4x4 dual cab utility cost $38,173[1] new, life of 10 years and 300,000 km fuel consumption 10 L/100 km [2] advisor time at $70/h farmer time at $50/h
		3	monitoring of seedling production at nurseries (2 or 3) by advisor to confirm supply	10%	travel time 2 h + vehicle + distance of 150 km + 3 h at nurseries	advisor: vehicle and rates as for row 2. 3 visits to nurseries each nursery inspection relates to the seedlings for 10 mallee sites, so 10% of this input is allocated to each site
2	Site preparation	4	site supervision and contract marking out	100%	advisor: + travel time 0.75 h + vehicle + distance of 25 km round trip + on-site time 5 h farmer: + time 2 h	advisor: vehicle and rates as for row 2. farmer time at $50 h
		5	earthworks by contractor or farmer one row ripped at a time	100%	ripping of planting rows + tractor ripping for 17 h + travel time on site 2 h + preparation and clean-up 2 h	169 kW front wheel assist tractor, e.g. JD 7230R cost $180,000[3] new; life of 10,000 h work rate 3 km/h at 1700 engine rpm; fuel consumption 30 L/h operator time at $35/h

[1] List price from redbook.com.au for a 2012 Toyota Hilux SR KUN26R 4-door crew cab utility: $41,990. Cost is $38,173 excluding GST. Also excludes dealer delivery, stamp duty and on-road costs.
[2] Combined fuel economy (urban + extra urban) of 8.3 L/100 km from redbook.com.au, increased to 10.0 L/100 km to account for paddock work.
[3] Advice on tractor type and list price courtesy of Shane Potter, GreenlineAg, Pingelly, WA. Price does not include GST.

Step no.	Operation	Row no.	Job description	Probability of job	Input	Description of input
2	Site preparation	6	rip line conditioning for planting, required on cloddy soil types note: if required more commonly, likely to be incorporated in step 5 by modifying ripping equipment	10%	harrows or similar drawn by farm tractor for 4 h + travelling time 1 h + preparation and clean-up 2 h	50 kW general purpose tractor e.g. Kubota M40. cost $40,000[4] new; life of 10,000 h work rate 6 km/h at 1700 engine rpm; fuel consumption 15 L/h harrows set cost $1,500[5], life 6,000 h approx. operator time at $35/h
		7	weed control	100%	pre-planting knockdown and residual herbicide treatment assumes double row belt is sprayed in a single pass (6 m x 25 km = 15 ha) + heavy 4x4 utility with spray rig for 2 h + travel 1 h + preparation and cleanup 2 h + herbicide treatment	4.5 L 150 kW diesel 4x4 heavy utility with boom spray. Ute cost $59,764[6] new, life of 10 years and 300,000 km fuel consumption 15 L/100 km[7] Boom-spray – mounted in tray of heavy utility cost $8,800 new, life 4,000 hours approx[8]. work rate 12.5 km/h travel to site and between sites at 30 km/h operator time at $35/h 1 L/ha of glyphosate (450 g/L glyphosate as the isopropylamine salt) group M herbicide 4 L/ha of simazine (500 g/L simazine) group C herbicide (triazine group) 10 g/ha metsulfuron methyl 600g/kg active ingredient, group B herbicide

[4] Based on Internet brochure for Kubota M40 series tractors. Does not include GST.
[5] Average price, based on price list by Murray Agricultural Equipment, Victoria. Note there is a wide range of equipment for different circumstances at various prices. Excludes GST.
[6] List price from redbook.com.au for a 2012 Toyota Landcruiser GX VDJ79R 2 door cab chassis: $62,240 + $3,500 estimate for steel tray fitted (information courtesy of Mandurah Toyota). After deducting GST, total cost is $59,764. Also excludes dealer delivery, stamp duty and on road costs.
[7] Manufacturer's combined fuel economy (urban + extra urban) of 11.5 L/100 km, increased to 15.0 L/100 km to account for paddock work.
[8] List price courtesy of Kevin Kentish, Spraymaster Spray Shop, Welshpool WA, for Hardi slip-on 600 L unit ($4300) + 6 m spray boom ($1250) + attachment gantry ($650) + hose reel, 50 m hose and spray gun ($1150) + freight ($450). All prices before GST. Note: add $1,000 approx. to upgrade to 12 m boom spray.

<table>
<tr><th>Step no.</th><th>Operation</th><th>Row no.</th><th>Job description</th><th>Probability of job</th><th>Input</th><th>Description of input</th></tr>
<tr><td rowspan="2">3</td><td rowspan="2">Planting</td><td>8</td><td>delivery of seedlings from nursery to site
+ empty tray pickup after planting</td><td>100%</td><td>seedling delivery:
+ travel time 2 h
+ vehicle
+ distance of 100 km round trip
+ 2 h unloading
tray pickup:
+ travel time 1 hr
+vehicle
+ extra distance of 50 km</td><td>4.9 L 130 kW diesel light truck (mass 3 T, GVM 8 T).
cost $69,364[9] new, life of 10 years and 300,000 km.
fuel consumption 18 L/100 km
driver time at $30/h</td></tr>
<tr><td>9a</td><td>hand planting of seedlings by contractor</td><td>50%</td><td>advisor: 1 trip
travel time 0.75 h
+ vehicle
+ distance of 25 km round trip
+ on-site time 4 h
tree planting team: 5 planters using hand tools
travel time 1 hr per day (or part)
+vehicle
+ distance of 25 km round trip[10] per day (or part)
+ planting time 11 h (2 days for travel inputs)</td><td>advisor: vehicle and rates as for row 2

tree planters:
3.0 L 126 kW turbo diesel 4x4 dual cab utility as for row 2
team of 5 plants 16,000 seedlings per 7 h day
tree planter time at $30/h (for planting time only)</td></tr>
</table>

[9] New price based on Mitsubishi Fuso Canter Model FE85D-Z of $69,300 + $7,000 approx for custom-built back with side tarpaulins suitable for seedling transport (information courtesy of Bunbury Truck Centre). Total cost is $69,364 excluding GST, and excluding dealer delivery, stamp duty and on road costs.
[10] Includes travel to farm and travel to accommodation (or home), plus use of vehicle to ferry seedlings around farm to planting sites.

Step no.	Operation	Row no.	Job description	Probability of job	Input	Description of input
3	Planting	9b	semi-mechanical planting of seedlings	50%	advisor: same as row 9a general purpose farm tractor and semi-mechanised tree planter: delivery of tree planter tree planters: travel time 1 hr per day (or part) +vehicle + distance of 25 km round trip[11] per day (or part) + tractor 16 h planting + 2 h on-site travel + planting machine 16 h + planting time 16 h + 2 h on-site travel (2 days for travel inputs)	advisor: vehicle and rates as for row 2 50 kW general purpose tractor, as for row 6 mechanised seedling planter cost $7,500[12] new, life of 6,000 h transport tree planter to site $200 tree planters: 3.0 L 126 kW turbo diesel 4x4 dual cab utility as for row 2 two people planting 12,500 seedlings per 8 h day tractor operator time at $35/h planting assistant time at $30/h
4	Post-planting	10	monitoring of newly planted seedlings by advisor	33%	advisor: 4 inspections, each: travel time 0.75 h + vehicle + distance of 25 km + on-site time 4.5 h	advisor: vehicle and rates as for row 2. each trip involves a visit to 3 sites, so 33.3% of this input is allocated to this project
		11	monitoring of newly planted seedlings by farmer	100%	farmer: 4 inspections, each: vehicle + distance of 10 km + on-site time 1.5 h	farmer: vehicle and rates as for row 2 farmer time at $50/h

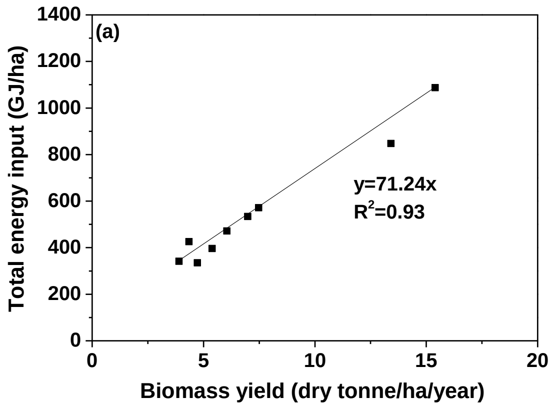
[11] Includes travel to farm and travel to accommodation (or home).
[12] Source: Internet sites for different manufacturers and models. Approximate mid-range cost for single-seat planting machine, including delivery cost, but excluding GST.

Step no.	Operation	Row no.	Job description	Probability of job	Input	Description of input
4	Post-planting	12	spring weed control, over-spraying with selective herbicides	4%	herbicide treatment: assumes double row belt is sprayed in a single pass (6 m x 25 km = 15 ha) heavy 4x4 utility with boom spray for 2 h (assumes single-pass spraying) + travel to and between sites 1 h + preparation and cleanup 2 h + selective herbicides	4.5 L 150 kW diesel 4x4 heavy utility with boom spray as for row 7 work rate 12.5 km/h travel rate 30 km/h operator cost at $35/h 0.5 L/ha of Lontrel broadleaf selective (300 g/L clopyralid) group I herbicide 10 g/ha of Eclipse radish selective (714 g/kg Metosulam) Group B herbicide 0.2 L/ha of Verdict 520 grass selective (520 g/L haloxyfop-R-methyl) group A FOPS herbicide
		13	insect control by farmer	5%	insecticide treatment: sprayed in a single pass with a 1.8 m swathe over each tree row (2 x 1.8 m x 25 km = 9 ha) 4x4 utility and boom spray as per row 12 + insecticide treatment	4x4 heavy utility with boom spray: inputs same as row 12 0.2 L/ha Dominex (100 g/L alpha-cypermethrin) Group 3A insecticide
		14	second year weed control	20%	4x4 utility and boom spray as per row 12 + overspray residual herbicide	4x4 heavy utility with boom spray: inputs same as row 12 4 L/ha of simazine (500 g/L simazine) group C herbicide (triazine group)
5	Post-harvest	15	supply and apply fertilizers after each biomass harvest	100%	farm tractor for 3 h + 2 h travel time to sites and between sites + preparation and cleanup time 2 h + phosphate fertilizer + nitrogen fertilizer + potassium fertilizer	50 kW general purpose tractor, as in row 6 work rate 8 km/h, fuel consumption 15 L/h operator cost of $35/h 832 kg/ha Urea 200 kg/ha of di-ammonium phosphate 386 kg/ha of muriate of potash

Table S3. Site specific details for the life cycle inventory of mallee biomass in nine sites

Parameter	Alexander	Bird	Fuchbichler	Morrell	Quicke	Stanley	Strahan	Sullivan 1	Sullivan 2
Site number	1	2	3	4	5	6	7	8	9
Biomass yield (dt/ha/y)	15.4	5.4	4.7	6.0	4.4	7.5	3.9	13.4	7.0
Distance to site from regional centre (km)	15	49	111	93	110	128	86	31	33
Distance to nursery from regional centre (km)	56	56	83	56	56	83	83	10	10
Distance to nursery from site (km)	55	33	37	112	70	45	48	31	33
Advisor travel time from regional centre to site (hours)	0.3	1.1	2.5	2.1	2.4	2.8	1.9	0.7	0.7
Advisor travel time from regional centre to nursery (hours)	1.2	1.2	1.8	1.2	1.2	1.8	1.8	0.2	0.2
Travel time from nursery to site (hours)	1.6	0.9	1.1	3.2	2.0	1.3	1.4	0.9	0.9
Harvest cycle period (years)	4	5	5	5	5	4	4	4	4
Row number	2	3	2	2	2	2	3	6	6
Belt width (m)	6	8	6	6	6	6	8	14	14
Space between trees within rows (m)	2	2	2	2	2	2	2	2	2
Number of trees per m of belt	1	1.5	1	1	1	1	1.5	3	3
Number of trees per km of belt	1,000	1,500	1,000	1,000	1,000	1,000	1,500	3,000	3,000
Standard planting in number of trees	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000
Standard planting (km)	25.0	16.7	25.0	25.0	25.0	25.0	16.7	8.3	8.3
Area of belt per km of length (ha)	0.6	0.8	0.6	0.6	0.6	0.6	0.8	1.4	1.4
Standard planting area (ha)	15.0	13.3	15.0	15.0	15.0	15.0	13.3	11.7	11.7
Number of trees per ha	1,667	1,875	1,667	1,667	1,667	1,667	1,875	2,143	2,143
Fertilizer (urea) kg applied once in each harvest cycle	799	349	267	441	415	420	214	553	380
Fertilizer (DAP) kg applied once in each harvest cycle	163	78	104	116	77	89	46	187	71
Fertilizer (MOP) kg applied once in each harvest cycle	346	149	170	165	179	226	101	293	155

3. Correlations between biomass yield and total life cycle energy inputs and GHG emissions



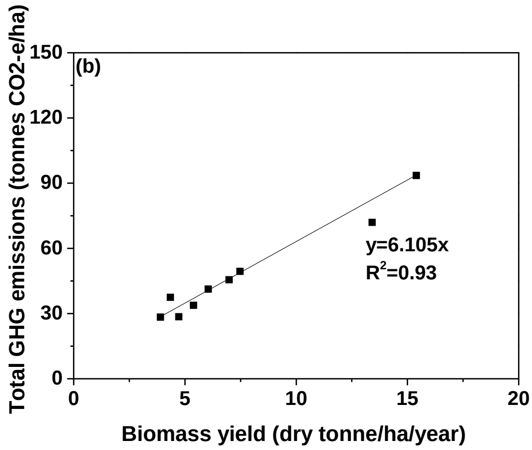


Figure S4. Correlations between biomass yield and total life cycle energy input (a) and GHG emissions (b) during biomass production.

4. Sensitivity analysis results

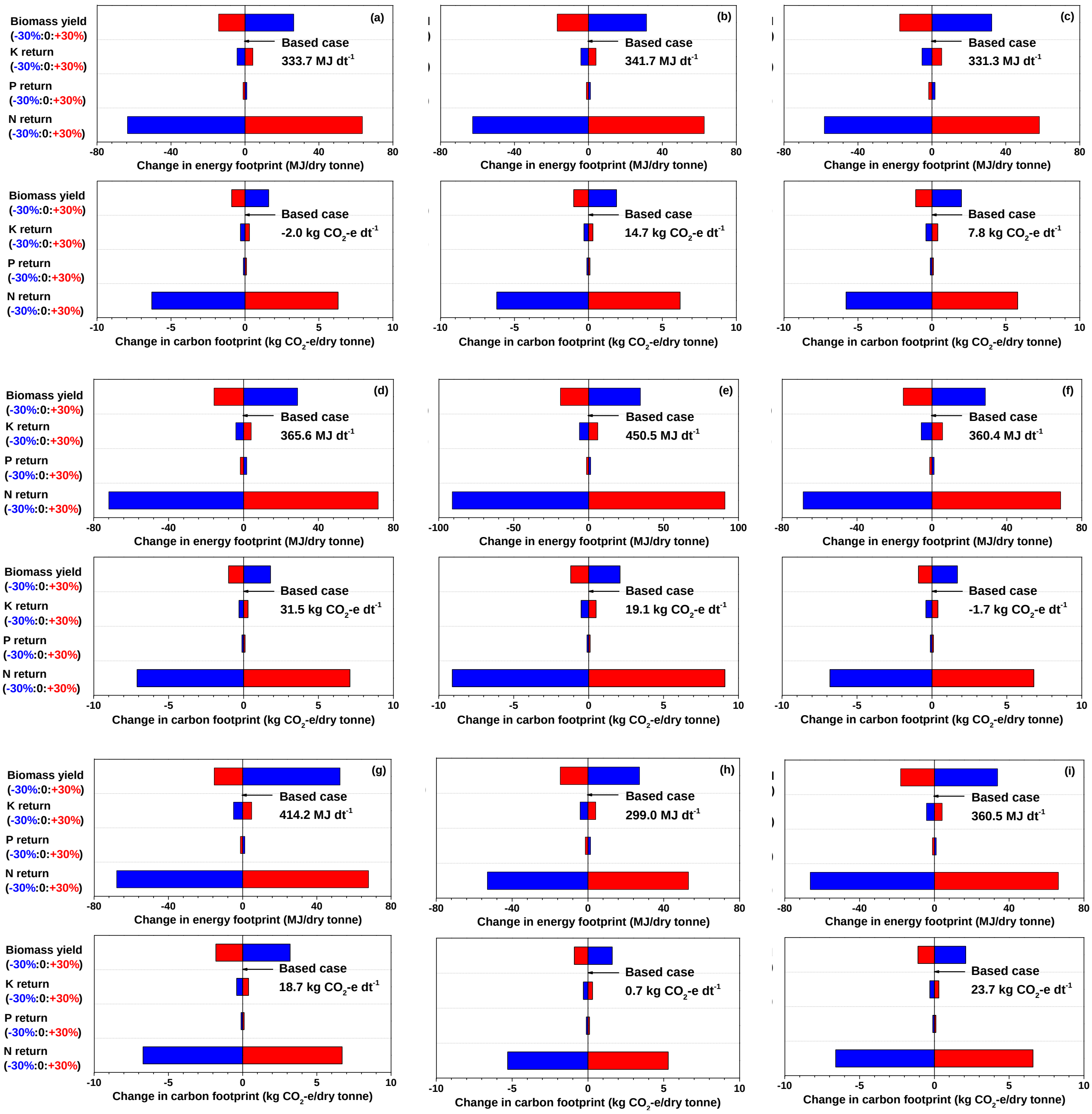


Figure S5. Sensitivity analysis of life cycle energy and carbon footprints to the inputs of fertilizers (N, P, K) and biomass yield for all nine sites. (a) Site 1 - Alexander; (b) Site 2 - Bird; (c) Site 3 - Fuchbichler; (d) Site 4 - Morrell; (e) Site 5 - Quicke; (f) Site 6 - Stanley; (g) Site 7 - Strahan; (h) Site 8 - Sullivan 1; and (i) Site 9 - Sullivan 2.

References

(1) *ISO 14040 - 14043, Environmental management - life cycle assessment. International Organization for Standardization: Geneva, Switzerland.*; 1997.

(2) Wang, M. *Greehouse gases, regulatied emissions, and energy use in transportation (GREET) model, 1.8b*, UChicargo Argonne, LLC: 2008.

(3) ABS *Towards the Australian Envrionmental-Economic Accounts*; Australian Bureau of Statistics: 2013.

(4) Giles, R. C.; Harris, H. D., Developing a biomass supply chain for new australian crops. In *Short rotation crops for bioenergy; Proceedings of the IEA Bioenergy Task 30 Conference*, Tauranga, New Zealand, 1-5 December, 2003.

(5) Mendham, D.; Bartle, J.; Peck, A.; Bennett, R.; Ogden, G.; McGrath, G.; Abadi, A.; Vogwill, R.; Huxtable, D.; Turnbull, P. *Management of mallee belts for profitable and sustained production*; CSIRO, WA DEC and the CRC for Future Farm Industries, supported by the Australian Government through the Second Generation Biofuels Research and Development Grant Program: May 2012.

(6) Schmidt, E.; Giles, R.; Davis, R.; Baillie, C.; Jensen, T.; Sandell, G.; Norris, C. *Sustainable biomass supply chain for the mallee crop industry*; Rural Industries Research and Development Corporation, Australian Government: July 2012.

(7) Cherubini, F.; Bird, N. D.; Cowie, A.; Jungmeier, G.; Schlamadinger, B.; Woess-Gallasch, S., *Resources, Conservation and Recycling* **2009,** 53, 434-447.

(8) Eggleston, S.; Buendia, L.; Miwa, K.; Ngara, T.; Tanabe, K., *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4, Agriculture, Forestry, and Other Land Use*. 2006.

(9) Lal, R., *J Soil Water Conserv* **2008,** 63, 113-118.

(10) *National Inventory Report 2008 Volume 1-3, Australian National Greenhouse Accounts, the Australian Government Submission to the UN Framework Convention on Climate Change*; Department of Climate Change and Energy Efficiency, Australian Government: May 2010.

(11) Richards, G. P. *The FullCAM carbon accounting model: Development, calibration and implementation for the national carbon accounting system*; Australian Greenhouse Office: February 2001.

(12) Wu, H.; Fu, Q.; Giles, R.; Bartle, J., *Energy Fuels* **2008,** 22, 190-198.

(13) Bartle, J. R.; Abadi, A., *Energy Fuels* **2010,** 24, 2-9.