LIFE CYCLE ANALYSIS OF WOOD PELLET FROM SRC THROUGH DIRECT MEASURING OF ENERGY CONSUMPTION

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ABSTRACT: In Italy wood pellet is experiencing some difficulties because of the lack of sawdust (the principal raw material) at cheap prices. For this reason it is interesting to evaluate the possibility of producing this biofuel from Short Rotation Forestry. The paper describes the environmental impact assessment of wood pellet production from dedicated energy crops (poplar) through a Life Cycle Analysis carried out using a detailed LCA software (Simparo 6.0). The life cycle was considered from the agricultural phase to the grinding and pelletising process ending with the combustion of the pellet in a household boiler. Transportation of wood and pellets were also considered. In particular, for the pellet production process mass and energy flows were measured on an existing Italian pelleting plant, while other data were obtained from the Literature.
The study shows that agricultural operations account for most of the environmental impact and that the overall impact is considerably less than the one caused by natural gas heating.
KEYWORDS: Life Cycle Assessment (LCA), pellets, Short Rotation Coppice (SRC)

1 INTRODUCTION

Wood Pellet (WP) is a renewable energy product which is gaining popularity around the world as biofuel, while in Italy the pellet is still in the take off phase, requiring also specific set of rules to classify the product and its quality. Moreover WP can be obtained from different feedstocks, such as residual biomass from agricultural or industrial processes, forestry pruning and dedicated crops. These latter, in particular, are gaining interest because of the poor availability of sawdust from forestry residuals, but WP from energy crops may require more energy in the overall process from wood to pellet, than the quantity obtained from the combustion of the biofuel.

From these premises, it seemed necessary to carry out the Life Cycle Assessment (LCA) of WP from Short Rotation Coppice (SRC), namely poplar, to provide an objective procedure to evaluate the energetic and environmental expenses. The resulting pellet is not high quality, in accordance with CTI–R04/5 recommendation [1], because it is characterized by an ash content of 1,5% – 2,5%, being the raw material composed by wood chips with an important percentage of bark.

Mass and energy flows of the overall process were evaluated including SRC cultivation, pelletising, WP combustion, ash disposal and every transportation required.

The major difficulty of this study was to find data regarding the pelletising process, because no certain data about the various phases of the process was available in the Literature. Therefore one Italian pelletising plant was monitored during the production phase to measure the energy required in each phase of the process.

2 LIFE CYCLE ASSESSMENT

Life cycle assessment was carried out with the assistance of commercial LCA software package, SimaPro 6.0. It is an open structure program that can be used for different types of life cycle assessments. The production stage, the use stage and the end of life scenario can be specified in as much detail as necessary by selecting processes from the database and by building processes trees, which can be drawn by the program.

LCA studies are composed of several interrelated components: goal definition and scoping, inventory analysis, impact assessment, and improvement assessment (ISO 14040 [2]). In the following, each step is described with regard to this work.

2.1 Goal definition and scoping

The first stage is the ‘‘Goal definition and scoping’’, as described in ISO 14041 [3], and it includes the definition of the functional unit.

The aim of this work is to assess the environmental impact, on a life cycle horizon, of wood pellet utilisation for energy production (in particular heat production). The reference functional unit for the inventory analysis and impact assessment is the thermal energy production of 1 MJ. All the energy and mass flows in the inventory are normalized to this functional unit

The system under consideration in this study includes both the wood pellet production from SRC and the conversion of that biomass to thermal energy. Fig. 1 shows the general system boundaries for the scenario considered in this study. In particular it comprehends: wood chips production from dedicated energy crops (SRC, poplar), its transportation to the pelleting plant, its transformation into pellet, the transportation of pellets to the final user and their combustion in a small domestic boiler (22 kW), including the disposal of ashes. Energy crops production was also considered for a plantation with the following features:

- density: 10.000 cuttings/ha;
- cultivation period: 8 years;
- felling frequency: 2 years.

In particular the agricultural operations considered for the cultivation cycle, are shown in Table I [4].

Table I: Agricultural operations for poplar cultivation [3].

Agricultural operations	*Year*							
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
ploughing	x							
harrowing	xx							
surface dressing	x		x		x		x	
field dressing	x	x	x	x	x	x	x	x
planting	x							
herbicides pre	x		x		x		x	
herbicides post	x	x	x	x	x	x	x	x
cultivating	xx	xx	xx	xx	xx	xx	xx	xx
harvesting		x		x		x		x
tree levelling								x

2.2 Inventory analysis

Any product or service needs to be represented as a system in the inventory analysis methodology.

The inventory analysis is a quantitative description of all the flows of materials and energy across the system boundary either into or out of the system itself.

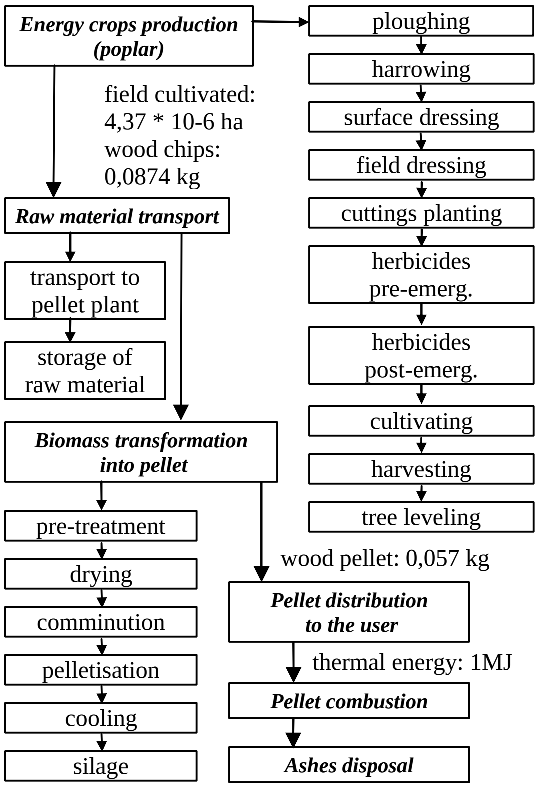

Figure 1: Production of thermal energy from wood pellet combustion. Data are referred to the functional unit (1 MJ).

2.2.1 Cultivation

Poplar cultivation process considered a biomass production ratio equal to 20 tons per hectare per year with a cultivation cycle of eight years. For this reason the process was considered for a standard year, in which each agricultural operation was counted a number of times equal to the average value in the eight years.
For each process the following quantities were considered, assuming literature data: the amount of machinery needed for a specific operation (operating machines and driving machines), fuel consumption for agricultural machines, amount of fertilizer and pesticide used, atmospheric emissions produced by diesel engines, heavy-metal emissions from tyre abrasion [5], ammonia, dinitrogen monoxide and NO_x air emissions from the application of fertilizers, phosphates water emissions from the application of fertilizers [6], VOC air emissions from the application of pesticides and soil pollution deriving from the remained of pesticides in the soil [7]. Type of machinery, fuel consumption, materials used and working times are listed in Table II. Cuttings are not taken into account because part of the harvested material is used for the next plantation.

2.2.2 Transportation and storage

The second phase is represented by the transportation of wood chips to the pelleting plant, assuming an average distance of 80 km, with a 28 tons lorry and characterized by a load factor equal to 47 %. The atmospheric, soil and water emissions (due to tyre abrasion) and fuel consumptions have been calculated referring to [8] which also considers for the construction phase of vehicle.

The next process is the storage of raw material at the pelletising plant: it is assumed that the movement of raw materials, inside the storage area, is carried out by a skid-steer loader (155 kW, load capacity of 5 m^3). Fuel consumption has been calculated using data privately referred and considering a load/discharge cycle of raw material with these characteristics:

- covered distance (there and back): 300 meters;
- average velocity: 10 km/h;
- average time for load or discharge: 10 seconds.

Inventory data for the production of this machinery was not available and for this reason it has been considered a skid-steer loader with 110 kW power [9].

2.2.3 Pelleting

Data regarding wood biomass transformation into pellet was not available in the Literature, not even with reference to the single processes. For this reason an Italian pelleting plant was contacted to evaluate mass and energy flows of the various steps. The plant is characterized by a production capacity of 2 tons/h. Table III shows the various sections of the plant:

- pre-treatment of raw material;
- drying (the heat source considered is a natural gas boiler which supplies 1000 kwh_{th} per ton of water evaporated; water evaporated is dispersed into the atmosphere);
- comminution (provided by two milling sections that grind raw material fine);
- pelleting (two pellet mills, powered by diesel engines, and each of them has a conditioning unit which is used to supply corn starch);
- cooling (pellets reach 70-80ºC and after pressing are cooled to 20ºC in a counterflow cooler);
- silage.

Electricity consumption of machineries was evaluated directly through an acquisition data system (Multiver 3SN Dossena) which carried out an energy measurement from analogic inputs, through amperometric pliers, for electric current, and, directly, for voltage. Each operation was monitored for a variable period of time according to the actual loading of the machine. Energy was then referred to the processed quantity.

Table III: Characteristics of the pellet plant examined and electricity consumptions measured by Multiver 3SN Dossena Instrument referred to functional unit.

Sections	*Installed Power (kW)*	*Electricity consumption (kWh/kg_{pellet})*	*Materials*
Pre-treatment	**10,27**	**0,0019**	
loading tank	5,5	1,00E-3	
vibrating screen	2,2	4,06E-4	
magn. separator	0,37	6,93E-5	
cup elevator	2,2	4,06E-4	
Drying	**100,9**	**0,0188**	
feeding tank	7,5	1,40E-3	
rotary drum	10	1,86E-3	Nat. gas:
exhaust fan	75	1,40E-2	7,22E-4
star valve	2,2	4,08E-4	$kWh/kg_{pell.}$
cup elevator	2,2	4,08E-4	
screw conveyor	4	7,47E-4	
Comminution	**202**	**0,0377**	
2 screw extract.	1,8 (*2)	3,36E-4 (*2)	
2 feed screws	2,2 (*2)	4,09E-4 (*2)	
2 hammermills	75 (*2)	1,40E-2 (*2)	
2 volum. pumps	22 (*2)	4,11E-3 (*2)	
Pelletisation	**16**	**0,0030**	

2 feed hoppers 2 conditioners 2 presses 2 screw convey.	2,2 (*2) 4 (*2) - 1,8 (*2)	4,11E-4 (*2) 7,52E-4 (*2) - 3,37E-4 (*2)	diesel: 9,9 g/ $kg_{pel.}$ cornstarch: 0,01 kg/ kg_{pellet}
Cooling screw extractor cooler	**4,8** 1,8 3	**0,0009** 3,38E-4 5,62E-4	
Silage vibrating screen cup elevator	**2,95** 0,75 2,2	**0,0006** 1,53E-4 4,47E-4	

Eventually the contribution of the construction of the plant main structures was taken into account considering only main materials and discarding energy consumptions for assembly. Table IV shows the infrastructures considered, the materials and their lifetimes.

Finally the impact of land occupation due to pelleting plant was considered for an occupied area of 1 ha.

2.2.4 Transportation to the user

Pellets, stored in silo, are distributed in bulk by trucks (gross weight 40 t, load factor 46%, distance 80 km) which unload the bio-fuel by blowing the pellets into the storage room of the user. Mass and energy flows were determined similarly as in 2.2.2.

2.2.5 Combustion

For the pellet combustion process, a 22 kW pellet boiler was considered, and mass and energy flows were calculated for the manufacturing of the boiler, the pipes for heat distribution inside the building, the heat accumulator, the storage silo and the pellet extraction system. Also in this case the energy necessary for the assembling of the items considered was not taken into account.

Table V shows the assumptions and the total amount of materials considered in this process together with the emissions into atmosphere produced by pellet combustion [10,11].

Table V Assumptions for combustion.

Materials	***Quantity***	***Category***	***Quantity***
rock wool	5 kg	usage	1600 h/y
cast iron	12 kg	efficiency	82 %
copper	5,6 kg	boiler lifetime	20 years
Stl low allw	500 kg	pellet cons.	8,8 tons/y
polyethylene	1,2 kg	silo supplies	2 per year
concrete	3,4 m^3	silo volume	6,8 m^3

Substance	***mg/MJ$_{thermal\ energy}$***
CO	146,34
TOC	3,66
CH4	0,67
PAH	0,07
particulate	19,51
NOx	85,37
NMVOC	0,49

The amount of electricity consumed by water circulation pump and the screw pellet extractor was assumed for 230 W that corresponds to a consumption of 0,0027 kWh/MJ_{th}.

2.2.6 Ash disposal

The last process considered is the disposal of ashes assuming an ash content of 2%, which corresponds to 1,05 mg of ashes per functional unit. Direct spreading on agricultural areas was chosen as disposal technique and this assumption has enabled to assume an avoided consumption of potassium fertilizer equal to 1,05 mg/MJ_{th}.

Dismantling and recycling of machineries and infrastructures were not considered throughout the study.

2.3 Impact assessment

Impact assessment was carried out considering eleven impact categories (carcinogens, respiratory organics, respiratory inorganics, climate change, radiation, ozone layer, ecotoxicity, acidification/eutrophication, land use, minerals, fossil fuels) classified into three further damage categories; Human Health (HH), Ecosystem Quality (EQ) and Resources (R). Finally, the application of weighting factors to determine the relative importance, or seriousness, of a category results may be represented as a single score in eco-indicator points (Pt).

In this study the impact assessment and characterisation has been performed by the LCIA method EcoIndicator 99. This method was preferred to others because it provides the most relevant impact assessment categories relative to this study. The index chosen for the impact assessment is the hierarchist's version with average weighting set, which represents the most balanced view amongst all the perspectives on nature.

3 RESULTS AND DISCUSSION

Tables VI and VII show the global eco-score (2.96 mPt: millipoint) for each damage and impact category.

It can be noted that the environmental impact on Human Health is much more important than the impact on Ecosystem Quality and Resources. Moreover, the impact related to Respiratory Inorganics and Fossil Fuels contribute most to the global eco-score. The impact category that weights most is pellet combustion, while for the second impact category the largest contribution is represented by energy crops production.

With reference to the distribution of the eco-score among the different macroprocesses, it can be observed that the environmental impact is mainly due to energy crops production (36,8% of the total impact) and biomass transformation into pellet (30%).

Table X: Contributions of the agricultural operations to the environmental impact of the energy crops production.

Agricultural operations	***Contribution (%)***
ploughing	1,15
harrowing	1,25
surface dressing	29,35
field dressing	48,37
cuttings planting	1,37
herbicides pre-emergency	0,62
herbicides post-emergency	1,65
cultivating	7,80
harvesting	3,18
tree levelling	5,26

In particular, among agricultural processes (Tab. X), it can be noted that surface dressing (29,4% of the energy crops production impact) and field dressing (48,4%) represent the major two contributions to the environmental impact of energy crops production. When considering the transformation of wood into pellet, the most important contribution is pelleting (61,2% of the overall impact), mainly because of diesel and corn starch consumption.

Moreover it seemed interesting to determine environmental burdens of WP production from SRC and of its combustion discarding infrastructures and machineries in the various processes, therefore taking into account only mass and energy flows. Table X and XI show that in this case the global score assumes a value of 2,52 mPt. Therefore discarding these inputs an error of 15% is committed.

3.1 Comparison with Natural Gas

Finally a comparison with the environmental impact of heat obtained from natural gas combustion was carried out assuming the following processes referring to SimaPro internal database [12]:

- extraction and production of gas onshore and offshore from Germany, Algeria, Netherlands and Russia;
- transportation to Italy through pipelines;
- distribution to consumers trough local pipe networks;
- combustion in a boiler (<100 kW).

Results show that heat produced from natural gas has a higher impact (4,83 mPt) than heat produced from wood pellet (2,96 mPt) mainly because of fossil resources depletion.

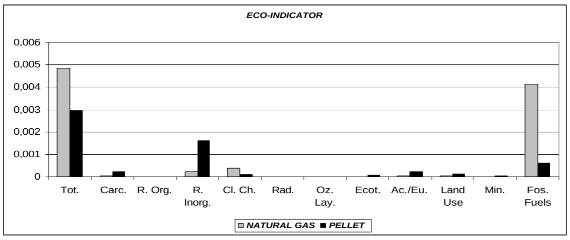

Figure 2: Environmental impact of wood pellet and natural gas subdivided in the impact categories (values in Pt).

In terms of energy consumption, considering only diesel, natural gas and electricity as inputs, it has been determined that are necessary 0,203 MJ of thermal energy to produce 1 MJ from pellet combustion.

4 CONCLUSIONS

The LCA analysis of producing household heat from Short Rotation Coppice (poplar) Wood Pellets (WP) was carried out considering the overall process from field growing to ash disposal and also the impact of construction materials for machinery. Data for each phase were obtained from the Literature and by directed measuring of energy consumption for the pelleting process.

Results show that main impacting phases are due to the agricultural process and the pelleting operation. When discarding the contribution of materials for machinery the reduction is around 13%. A final comparison with heat produced from Natural Gas shows a 38% lower impact of WP.

So it would have to stimulate the replacement of natural gas boilers with wood pellet boilers, which environmental burden could be further reduced by less use of chemical fertilizers in the life cycle of biofuel.

5 ACKNOWLEDGEMENTS

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Table II: Data summary for the agricultural operations.

Agr. operations	*Machinery*	*Fuel (kg/ha)*	*Materials (kg/ha)*	*Time (h/ha)*
ploughing	tractor (80 kW) + 2-furrow plough	41,550		2,340
harrowing	tractor (80 kW) + spring tine harrow	41,200		0,790
surface dressing	tractor (51 kW) + fertiliser spread	1,7900	NPK fertilizer (8-24-24): 500	0,160
field dressing	tractor (51 kW) + fertiliser spread	5,0300	urea: 218	0,450
cuttings planting	tractor (51 kW) + two-row planter	67,280		6,050
herbicides pre-emerg.	tractor (51 kW) + field sprayer	1,7900	Metolachlr 1,7 Linuron: 0,5 Pndmthlin: 0,8	0,160
herbicides post-emerg	tractor (51 kW) + field sprayer	13,530	Pyridate: 1,1 Fluazifop-p-butyl: 0,6	1,210
cultivating	tractor (51 kW) + rotary harrow	7,8100		0,700
harvesting	tractor (130 kW) + SRF harvester	109,15		1,590
tree levelling	tractor (80 kW) + spring tine harrow	240,40		13,36

Table IV: Characteristics and lifetimes of the pellet plant infrastructures, considered in the LCA analysis.

Sections	*Infrastructures Type*	*Materials*	*Lifetime (years)*
Pre-treatments	vibrating screen	Aluminium. 107,5 kg Steel low-alloy: 107,5 kg	50
	cup elevator, magnetic separator	Steel low-alloy: 700 kg	50
Drying	rotary drum	alum. wrought alloy: 640 kg alum. sheet rolling: 640 kg	10
	exhaust fan	aluminium: 1000 kg Steel low-alloy: 1000 kg	50
	Natural gas boiler	refractory: 70 kg, cast iron: 4200 kg, chromium stl: 230 kg Steel low-alloy: 190 kg, rock wool: 40 kg	20
	cup elevator, screw conveyor	Steel low-alloy: 700 kg	50
Comminution	2 hammermills	reinforced steel: 2500 kg, steel sheet rolling: 2500 kg	10
	2 feed screws, 2 screw extract.	Steel low-alloy: 700 kg	50
Pelleting	2 presses	Steel low-alloy: 4000 kg, sheet rolling: 4000 kg	10
	2 feed hoppers, 2 screw convey.	Steel low-alloy: 700 kg	50
Cooling	cooler	Steel low-alloy: 200 kg	15
	screw extractor	Steel low-alloy: 210 kg	50
Silage	vibrating screen	aluminium: 107,5 kg, Steel low-alloy: 107,5 kg	50
	silo (100 m^3)	glass fibre: 3800 kg, cast iron: 500 kg, reinforcing steel: 500 kg	25
	cup elevator	Steel low-alloy: 350 kg	50

Table VI: Simapro results for the damage categories.

Damage category	*TOTAL (Pt)*	*energy crops produc. (Pt)*	*raw material transp. (Pt)*	*biomass transf. into pellet(Pt)*	*pellet distrib. to the user (Pt)*	*Pellet comb. 22 kw (Pt)*
TOTAL	2,96E-03	1,09E-03	1,64E-04	5,76E-05	8,88E-04	7,62E-04
Human health	1,92E-03	5,82E-04	8,40E-05	2,35E-05	5,33E-04	6,99E-04
Ecosyst. quality	3,95E-04	1,45E-04	1,31E-05	4,50E-06	1,82E-04	5,06E-05
Resources	6,47E-04	3,64E-04	6,69E-05	2,96E-05	1,73E-04	1,31E-05

Table VII: Simapro results subdivided into different impact categories.

Impact category	*TOTAL (Pt)*	*energy crops produc. (Pt)*	*raw material transp. (Pt)*	*biom. transf. into pellet (Pt)*	*pellet distrib. to the use (Pt)*	*Pellet comb. 22 kw (Pt)*
TOTAL	2,96E-03	1,09E-03	1,64E-04	5,76E-05	8,88E-04	7,62E-04
Carcinogens	2,26E-04	1,72E-04	3,69E-06	1,99E-06	2,53E-05	2,34E-05
Resp. organics	9,38E-07	1,95E-07	9,23E-08	2,57E-08	4,71E-07	1,54E-07
Resp. inorganics	1,60E-03	3,62E-04	7,17E-05	1,80E-05	4,86E-04	6,67E-04
Climate change	8,62E-05	4,66E-05	8,42E-06	3,52E-06	2,03E-05	7,38E-06
Radiation	3,33E-06	5,36E-07	2,77E-08	1,24E-08	1,75E-06	1,00E-06
Ozone layer	4,79E-08	2,48E-08	5,86E-09	2,61E-09	1,43E-08	3,48E-10
Ecotoxicity	6,05E-05	2,76E-05	3,64E-06	1,72E-06	1,69E-05	1,06E-05
Acidif/ Eutroph.	2,11E-04	1,11E-04	8,52E-06	2,37E-06	5,03E-05	3,92E-05
Land use	1,23E-04	5,94E-06	9,25E-07	4,04E-07	1,15E-04	7,68E-07
Minerals	2,81E-05	7,80E-06	4,35E-07	2,33E-07	6,01E-06	1,36E-05
Fossil fuels	6,19E-04	3,57E-04	6,64E-05	2,93E-05	1,67E-04	-5,49E-07

Table XI: Simapro results subdivided into different impact categories (without infrastructures and machineries).

Impact category	*TOTAL (Pt)*	*energy crops produc. (Pt)*	*raw material transp. (Pt)*	*biom. transf. into pellet (Pt)*	*pellet distrib. to the user (Pt)*	*Pellet comb. 22 kw (Pt)*
TOTAL	2,57E-03	1,06E-03	1,64E-04	5,29E-05	7,35E-04	5,60E-04
Carcinogens	1,84E-04	1,63E-04	3,69E-06	2,15E-07	1,68E-05	-3,92E-07
Resp. organics	8,30E-07	1,74E-07	9,23E-08	2,46E-08	4,10E-07	1,30E-07
Resp. inorganics	1,39E-03	3,55E-04	7,17E-05	1,67E-05	4,04E-04	5,45E-04
Climate change	7,21E-05	4,55E-05	8,42E-06	3,38E-06	1,42E-05	5,48E-07
Radiation	2,98E-06	4,84E-07	2,77E-08	6,98E-09	1,62E-06	8,43E-07
Ozone layer	4,35E-08	2,43E-08	5,86E-09	2,55E-09	1,20E-08	-1,13E-09
Ecotoxicity	3,79E-05	2,48E-05	3,64E-06	1,47E-06	9,00E-06	-1,02E-06
Acidific/ Eutroph	2,03E-04	1,11E-04	8,52E-06	2,33E-06	4,41E-05	3,71E-05
Land use	1,17E-04	5,71E-06	9,25E-07	3,68E-07	1,11E-04	-1,19E-06
Minerals	5,71E-06	5,09E-06	4,35E-07	2,10E-08	1,20E-06	-1,04E-06
Fossil fuels	5,57E-04	3,49E-04	6,64E-05	2,83E-05	1,33E-04	-2,04E-05

Table XII: Simapro results for the damage categories (without infrastructures and machineries).

Damage category	*TOTAL (Pt)*	*energy crops produc. (Pt)*	*raw material transp. (Pt)*	*biomass transf. into pellet (Pt)*	*pellet distrib. to the user (Pt)*	*Pellet comb. 22 kw (Pt)*
TOTAL	2,57E-03	1,06E-03	1,64E-04	5,29E-05	7,35E-04	5,60E-04
Human health	1,65E-03	5,64E-04	8,40E-05	2,03E-05	4,37E-04	5,46E-04
Ecosyst. quality	3,57E-04	1,41E-04	1,31E-05	4,16E-06	1,64E-04	3,49E-05
Resources	5,62E-04	3,54E-04	6,69E-05	2,84E-05	1,34E-04	-2,14E-05