Title: Parametrized regionalization of paper recycling life-cycle assessment

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Abstract

Recycling is a commonly acknowledged strategy to reduce the environmental impacts linked to primary resource exploitation. Large regional variations can be observed in recycling processes' parameters, like efficiency, energy mix and treatment of rejects. Life-cycle assessment (LCA) is widely used to evaluate the environmental impacts of recycling processes, but existing studies are neither harmonized nor sufficient to provide a comprehensive geographical and technological coverage of recycling processes. The purpose of this research is to develop an efficient and iterative approach for the parametrized generation of semi-automated regionalized life-cycle inventories that take into account technological and geographical variabilities in the recycling sector. The regionalization framework is then applied to create a parametrized paper recycling regionalization tool. This tool is used in the results section to compare the national climate change impacts of recycling three paper grades. Results show a significant global warming impact variability between countries for recycled graphic paper (0.36 to 2.25 kg CO2-Eq/kg wastepaper recycled), newsprint (0.27 to 1.84 kg CO2-Eq/kg wastepaper recycled) and corrugated cardboard (0.28 to 1.68 kg CO2-Eq/kg wastepaper recycled) productions. A regionalized LCA of the international recycling of the mixed wastepaper exported from Quebec's (Canada) sorting centers is also performed with the tool and compared to the non-regionalized mixed wastepaper recycling process available in the *ecoinvent* database. Only nine midpoint ReCiPe impact categories remain environmentally advantageous compared to virgin paper production when applying the regionalization methodology,

compared to sixteen when using the *ecoinvent* process, illustrating how regionalization can substantially influence LCA results.

Keywords

Life-cycle assessment, recycling, regionalization, parametrization, wastepaper

Abbreviation list

BOD	Biological oxygen demand
CC	Corrugated cardboard
COD	Chemical oxygen demand
DS	Dissolved solids
GDP	Gross domestic product
GHG	Greenhouse gas
GP	Graphic paper
IEA	International Energy Agency
ISRI	Institute of Scrap Recycling Industries
LCA	Life-cycle assessment
LCI	Life-cycle inventory
MFA	Material flow analysis
NP	Newsprint
RoW	Rest of World
SS	Suspended solids

1. Introduction

Recycling is one of the prioritized strategies to establish a circular economy and to reduce the environmental impacts associated with virgin material extraction (Ellen MacArthur Foundation, 2017). When promoting a waste management strategy based on recycling, it is important to ensure that it is the best option among all treatment pathways, taking into account the benefits of replacing primary resources. Life-cycle assessment (LCA) methodology is frequently used to evaluate the environmental burdens and benefits of recycling processes (Laurent et al., 2014) and has demonstrated its usefulness in guiding environmental policy for waste management systems (Manfredi & Pant, 2011). Energy and material consumption, direct emissions, and the displacement of primary resource use are key factors when evaluating the environmental impacts of a recycling technology (Viau et al., 2020). These factors are highly dependent on the choice of the type of recycling technology and on the geographical context (Brogaard et al., 2014).

Before China announced an import ban on various types of waste in July 2017, it received more than 50 % of global wastepaper exports, mainly from high-income countries. From 2016 to 2020, China's wastepaper imports dropped by 76 %, forcing exporting countries to find alternatives (United Nations, 2016, 2020). Low-capacity paper recycling mills and the decreasing demand for paper products in developed countries have led to resort to short term solutions based on landfilling, incineration and exportation to developing countries with high demand for raw materials and low recycling costs (Qu et al., 2019; Rahman & Kabir, 2010). In 2019, 17 % of the 285 million tons of wastepaper produced worldwide were exported to be recycled (FAO, 2019). An example of the globalisation of wastepaper flows is the economy of the province of Quebec in Canada. The province recycles only 10 % locally, and exports wastepaper to 38 international regions for recycling, principally India (52 %) and the United States (23 %) (Statistics Canada, 2020). Recycling of wastepaper raises concerns regarding environmental emissions and material and quality losses, particularly in low-income countries. Amongst other factors, highly contaminated feedstock, low recycling rates, informal recycling and permissive environmental regulations exacerbate the environmental impacts of these recycling systems (Bleck & Wettberg, 2012; Confederation of Indian Industry, 2020; Rahman & Kabir, 2010; Tong et al., 2021). The diversification of destinations for recyclable waste exports complexifies the assessment of the environmental footprint of global recycling systems. In short, wastepaper recycling and the challenges faced by this industry are a global affair.

Merrild, Damgaard and Christensen (2008) illustrated the technological dependency of the results of LCA studies about recycling processes, by assessing the global warming impacts of different combinations of European paper recycling technologies and substituted virgin paper production technologies. The results showed large variations of greenhouse gas (GHG) emissions among the tested combinations, mainly due to differences in energy and electricity consumption (Merrild et al., 2008). Sevign´e-Itoiz and colleagues (2015) assessed the GHG emissions of the Spanish paper and cardboard recycling system, integrating material flow analysis (MFA) with LCA. They concluded that international trade and end-markets play a significant role in GHG emissions quantification (Sevign´e-Itoiz et al., 2015).

LCA studies that take into account international wastepaper trades are scarce (James, 2012); existing studies often focus on a particular technology in a particular region. Laurent et al. (2014) reported the geographic distribution of 222 waste management LCA studies performed between 1995 and 2012, including 117 studies comprising recycling processes. The authors concluded that most recycling studies addressed processes in North America, western Europe, China and Australia, and little to no studies originated from eastern Europe, South America, Africa and Asia, excluding China (Laurent et al., 2014). A lack of process technological regionalization and an exclusion of international trade flows can lead to oversimplified LCA studies unable to effectively guide policy implementation. With disparate efficiencies, raw material quality and use, use of utilities, use of chemicals, quality of recycled material and end-markets, LCAs performed in different developed countries are inadequate to represent many developing countries' recycling systems, and their use for this purpose will likely lead to a negative bias in environmental impact estimates.

Efforts have been undertaken independently to capture the environmental impacts of paper recycling in specific regions: Finland (Dahlbo et al., 2005a, 2007; Dahlbo et al., 2005b), Sweden (Finnveden et al., 2005; Moberg et al., 2005), China (Hong & Li, 2012; Liang et al., 2012), Denmark (Manfredi et al., 2011; Merrild et al., 2012; Merrild et al., 2008; Wang et al., 2012), Austria (Salhofer et al., 2007), United Kingdom (Wang et al., 2012), Spain (Sevign´e-Itoiz et al., 2015) and Italy (Arena et al., 2004). Amongst these reported studies, results diverge largely depending on the recycled paper grades produced, formulated assumptions and methodologies, e.g., system boundaries and coproduction modeling, as well as geographic context. Concerning paper recycling data availability in the *ecoinvent* database, the 3.7.1 version includes recycling processes for three main grades of paper, namely: graphic paper (GP), newsprint (NP) and corrugated cardboard (CC) (Wernet et al., 2016), but paper recycling models in this database are all based exclusively on European data. The *global* paper recycling models rely on global weighted averages for provision of certain inputs (e.g., wastepaper input, chemicals production, electricity use, energy use and waste disposal) and do not allow for regional breakdown since they use the same numerical values as the European processes. These isolated recycling modeling efforts in LCA literature and in the *ecoinvent* database are far from offering a convenient and consistent international coverage. Moreover, the results of these studies are not harmonized and cannot be used conjointly to assess the environmental impacts of the global recycling system of a country exporting wastepaper to diverse international destinations. And yet, aiming to obtain detailed primary data to model every national recycling system for every material type individually is a utopic and unattainable objective, and would likely lead to unharmonized and thus unusable results. There is an undeniable tension between the technological and geographical coverage by LCA studies and the effort needed to obtain representative data. A more efficient modelling approach is needed.

This study is part of a broader research effort towards the development of sectorial parametrization frameworks and tools. A sectorial LCA parametrization approach consists in selecting relevant variable parameters and creating a general life-cycle inventory (LCI) in a particular sector, which can be adapted to different contexts (e.g., geographies, technologies, temporality) by modifying the values of the parameters. This approach can be useful to represent multiple process variants in a more agile, accessible and efficient way than the individual approach comprising an intensive data collection process every time a new scenario has to be tested (Mueller et al. 2004). As concluded by Cooper et al. (2012), parametrization is also "a powerful way to ensure transparency, usability, and transferability of LCI data" (Cooper et al., 2012). Existing parametrized LCA models represent many sectors: aircraft production and operation (Dallara et al., 2013), product and building design (Basic et al., 2019; Kamalakkannan & Kulatunga, 2021; Niero et al., 2014; Vandervaeren et al., 2019), forest carbon fluxes according to carbon pools and forest management features (De Rosa et al., 2016), transportation (Jang et al., 2020; Kannangara et al., 2021; Khan, 2021; Lee & Thomas, 2017; Manjong et al., 2021; Sacchi et al., 2022) and photovoltaic energy production (Bracquene et al., 2018), to name a few. In the waste management sector, Doka (2021) pioneered a parametrization approach with a regionalization tool that assesses the life-cycle impacts of open burning, open dumping and different types of landfill technologies according to climate, technical parameters and waste characteristics (Doka, 2021). To our knowledge, broadly applicable parametrized LCA models and tools remain to be developed in the recycling sector.

The objective of this study is to develop an efficient and iterative approach for the parametrized generation of semi-automated LCIs that take into account technological and geographical variabilities in the recycling sector. Such an LCI regionalization framework systematizes the integration and harmonization of primary data, geographical extrapolations, and technology models, so as to efficiently and iteratively reduce the uncertainties of global recycling LCAs due to data scarcity, and to provide a comprehensive geographical and technological data coverage of recycling processes. This study also aims to produce a parametrized and collaborative tool based on the proposed methodological framework to perform regionalized LCAs of international paper recycling systems. This research facilitates the work of LCA practitioners in the recycling sector, by offering a framework for parametrized and regionalized LCI generation, and a parametrized and collaborative tool for systematic regionalized paper recycling LCI generation.

2. Methods and data

2.1 Methodology overview

Fig. 1 summarizes the general methodological framework used to select process parameters and to collect and estimate regionalized data for the recycling sector. The method starts by determining the scope of the study. Recycling process parameters to be regionalized are selected based on their potential variability due to technological or geographical factors (step 1, Fig. 1). A screening analysis is then performed on these parameters to determine to what extent they influence LCA results (step 2, Fig. 1). For parameters having a non-negligible impact on LCA results, their technological and geographical variability is characterized to guide data collection and estimation (step 4, Fig. 1). Data is then collected or estimated for every parameter and every country with recycling installations by minimizing the indicator scores according to the pedigree matrix (steps 5–8, Fig. 1). Finally, data quality is evaluated through an iterative process (steps 9–12, Fig. 1).

These methodological steps systematize and frame the traditional data collection and estimation process to generate regionalized LCIs for the recycling of different material types, by offering guidance for the choice of process parameters, for the classification of these parameters according to the granularity of data that need to be collected, and for identifying the best strategy to estimate missing data. In this study, it is applied to the paper recycling sector to create an LCI regionalization tool. Each methodological step included in Fig. 1 and its application for the construction of the tool are detailed step by step in sections 2.2 to 2.4.

2.2 Scoping

2.2.1 Definition of system boundaries

General method

The first step in Fig. 1 includes the definition of system boundaries. For coproduction modeling, the substitution approach from Vadenbo et al. (2017) is recommended. The practitioner must determine which multiplicative parameters constituting the substitution potential will be included in the study.

Application to the paper recycling regionalization tool

The chosen system boundaries of the paper recycling process include the transport from the sorting facility to the recycling facilities, the recycling process, the treatment of solid waste, and the substitution of virgin material. Fig. 2 illustrates the studied system and its boundaries. The chosen functional unit is “Recycling 1 kg of pre-sorted wastepaper bale into a specific product grade (GP, NP or CC)”. Substitution modeling is achieved by using the framework developed by Vadenbo and colleagues (2017), estimating the physical resource potential (U_{rec}) from the initial wastepaper bale composition, the technical resource recovery efficiency (η_{rec}) from the recycling process efficiency, the substitution ratio ($\alpha_{rec:disp}$), considered as a process parameter to be regionalized, and the market response (π_{disp}), assumed to be equal to 1 (Vadenbo et al., 2017). This last factor means that we assume consumers show no preference for the origin (primary or secondary) of a material of a given quality, and no price effect or other influence on demand are taken into account.

2.2.2 Preliminary selection of process parameters

General method

The first step in Fig. 1 also includes the selection of the process parameters to be regionalized. From the description of the studied recycling process, the practitioners should list comprehensively every process parameter that may vary according to the region where recycling is performed. A useful strategy to breakdown a technology’s life cycle into a finite number of contributors is the LiSET method (Hung et al., 2018). This method can be used to identify the regionalizable parameters likely to influence the environmental impacts of the studied recycling process.

Application to the paper recycling regionalization tool

Based on the LiSET method and on the paper recycling process description, 13 process parameters are assumed to have a potential influence on the LCA impacts due to their regional variability (step 1, Fig. 1): *Efficiency and solid waste production, Electricity use, Electricity mix, Energy use and direct air emissions, Energy mix, Chemicals use, Chemicals mix, Water use and wastewater production, Direct emissions to water, Sludge treatment technology mix, Other solid waste treatment technology mix, Virgin material input* and *Substitution ratio*. The application of the LiSET method for the selection of the parameters is detailed in supplementary information S1. The *Chemicals mix* parameter is neglected in the subsequent steps due to lack of data.

2.2.3 Screening analysis on process parameters

<u>*General method*</u>

The second step in Fig. 1 consists in performing a sensitivity analysis on the process parameters selected in step 1, between lower bounds and upper bounds defined from literature data, to determine if regional variations of each process parameter are likely to have a significant influence on LCA results. Some assumptions need to be made by the practitioners, including the choice of the reference recycling process on which to perform the sensitivity analysis (we suggest choosing a *global* process from *ecoinvent*), the impact characterization method, the maximum impact variation calculation method, and the maximum impact variation threshold.

<u>*Application to the paper recycling regionalization tool*</u>

For the construction of the tool, recycled GP, NP and CC *global* production processes from *ecoinvent* are used to perform the analysis. For each process parameter, a lower bound and an upper bound are defined from literature data (see supplementary information S2). Sensitivity analyses are performed for each process parameter and each corresponding paper grade, and the *ReCiPe* midpoint impact characterization method is chosen. The maximum impact variation (*V*) corresponds, among all the chosen impact characterization categories, to the largest relative difference between the impact of the analysis carried with the lower bound and the impact of the analysis carried with the upper bound. The maximum impact variation (*V*) between the lower and the upper bound LCAs is computed using equation (1):

$$V = MAX_i \left(\frac{|X_{L,i} - X_{H,i}|}{MAX(|X_{L,i}|, |X_{H,i}|)} \right) \quad (1)$$

where $X_{L,i}$ is the lower bound result for every midpoint *ReCiPe* impact i and $X_{H,i}$ is the upper bound result for every midpoint *ReCiPe* impact i.

In the present case study, a threshold of 15% is chosen on *V* to determine if the regional environmental impact variation warrants a detailed regionalization. For process parameters with *V* ≤ 15%, the value of the *global ecoinvent* process, for any geography, is used to create the model (step 3, Fig. 1). The lower bound, upper bound, data sources and the result of each sensitivity analysis are presented in supplementary information S2.

Results from the sensitivity analysis show that the variation of all process parameters, except for most emissions to water, has a significant impact on LCA results. No impact variability is observed for most types of emissions to water, even if the parameter's value varies, principally because the *ReCiPe* impact characterization methodology does not yet include impact characterization factors for all emissions to water. Therefore, the rest of the methodology is not applied to emissions to water, except *Direct phosphate emissions to water* for the production of recycled CC, which has a maximum impact variation above the threshold.

2.2.4 Characterization of process parameters' technological and geographical variability

General method

To orient data collection and estimation, the next methodological step consists in classifying the selected process parameters into two groups: technological variability, and geographical variability (step 4, Fig. 1). The parameters are further classified into two technological sub-categories, namely *grade-specific parameters* and *non-grade-specific parameters*. This distinction is used to evaluate the granularity of data collection needed in subsequent steps. The first group comprises the process parameters that do not vary according to product grade, for example the energy mix. The second group contains the process parameters that depend on product grade produced. For example, more chemicals are typically used when producing GP than CC. The geographically-sensitive parameters are also further classified into two sub-categories, namely *parameters linked to economic development* and *parameters linked to available resources and physical environment.* The first group contains process parameters linked to the country's technological and economic development, for example the efficiency of the recycling process. The second group encompasses the process parameters that depend on the country's available resources and physical environment, for example weather, climate or land availability. For instance, waste treatment technologies used in a country often reflect geographical characteristics, like the availability of usable land to practice landfilling of solid waste. This distinction is used to determine the most accurate way to estimate missing data. For example, if a parameter is correlated with economic development, the estimation of the parameter of a country with missing data should be done using data from a country with similar economic characteristics.

Application to the paper recycling regionalization tool

From the evaluation of *global ecoinvent* paper recycling processes and the comparison of process parameters for the production of GP, NP and CC, it was determined that *Electricity use*, *Energy use*, *Chemicals use*, *Water use and wastewater production* and *Direct emissions to water* varied significantly according to paper product grade. Based on literature and available data, *Efficiency and solid waste production*, *Electricity use*, *Energy use*, *Chemicals use*, *Water use and wastewater production* and *Direct emissions to water* were assumed to vary according to the economic development level (Confederation of Indian Industry, 2020; Devi et al., 2011), while *Electricity mix*, *Energy mix*, *Sludge treatment technology mix and Other solid waste treatment technology mix* were assumed to vary according to geographically available resources and physical environment. It was assumed that *Virgin material input* and *Substitution ratio* are not related to product grade, nor to geographic context, but rather to the quality of the input material and the desired and obtained quality of the product. The process parameters' classification into the four variability categories is illustrated in Fig. 3.

2.3 Data collection and estimation

General method

The next step consists in collecting and estimating data for every LCA-impacting process parameter to obtain a regionalized value or estimate for every country. The methodology prioritizes the use of data with the lowest indicator scores according to the pedigree matrix. The pedigree matrix was created to assess the quality of LCA data sources (Weidema & Wesnaes, 1996), and it constitutes the first step in semi-quantitatively evaluating their uncertainty (Muller et al., 2014). Two kinds of uncertainties are commonly taken into account with this approach: the intrinsic variability related to measurement uncertainties, activity specific variability or temporal variability and the uncertainty due to the use of imperfect data, related to the use of estimates or data lacking temporal, spatial or technological representativity (Muller et al., 2014). The pedigree matrix consists in attributing a score to five independent data characteristics, namely reliability, completeness, temporal correlation, geographical correlation and further technological correlation (Weidema et al., 2013). In the proposed framework, the evaluation of the uncertainties is restricted to geographical and technological correlations, because the other categories are not directly related to regionalization. Table 1 presents the pedigree matrix used and contains the description of the type of data corresponding to each indicator score for the geographical and technological variability categories from Weidema et al. (2013), as well as an example of each indicator score for the paper recycling sector for every variability category defined in section 2.2.4.

The first data collection step is to look for data with minimal indicator score(s) in the applicable variability categories for each process parameter and for every recycling country (step 5, Fig. 1). For example, the *Electricity use* parameter varies with economic development and is specific to paper grade. We should first look for data that is a representative national average (level 1 indicator score for geographical variability in Table 1) and that is specific to product grade (level 1–2 indicator score for technological variability in Table 1). This combination minimizes the indicator scores in both applicable variability categories and is thus considered an optimal score. Optimal score data can be used directly in the LCA model for these countries (step 6, Fig. 1). If many optimal indicator score datapoints are available for a process parameter in a country, the mean of the available values is used.

If optimal score data is not available, data estimation is required. Possible estimation data is therefore collected (step 7, Fig. 1). This data can be a process parameter's value for a country with similar economic characteristics (if the parameter is correlated with economic development) or with a similar physical environment (if the parameter is correlated with resources and physical environment). From the data collected, an estimate that minimizes the indicator score(s) of a specific parameter is chosen for each paper recycling country (step 8, Fig. 1). The geographical estimation method can be used to estimate data for parameters that depend on economic development. This method consists in approximating process parameters of countries with missing data with the data from the country with the most similar gross domestic product (GDP) per capita between all of the optimal indicator score data available. A similar method could be used for process parameters varying with resources and infrastructures.

Application to the paper recycling regionalization tool

The indicator scores of the data used to create the LCA tool for each process parameter and each applicable variability category are detailed in supplementary information S3. For some process parameters, we use existing databases containing data for most countries, for example the World Bank Group report for *Other solid waste treatment technology mix* (Kaza et al., 2018) or *ecoinvent* for *Electricity mix* (Wernet et al., 2016). For other parameters like *Efficiency* or *Electricity use*, data are mostly based on estimations from data reported in the literature, partly generated with the geographical estimation method.

Fig. 4 shows the results of the regionalization for the *Efficiency* process parameter. Fig. 4 a) illustrates the countries with an indicator score of 1 or 2 for the geographical correlation. For the remaining countries, the geographical estimation method was used, illustrated in Fig. 4 b).

The regionalized process parameters' values obtained for each country used in the paper recycling regionalization tool are accessible in supplementary information S4 (Provost-Savard, 2022a) and the datapoints and equations from which these regionalized parameters are derived are available in supplementary information S5.

2.4 Data quality evaluation

General method

In the *Scoping* phase, the desired level of certainty and confidence is (subjectively) defined in dialogue with all stakeholders. In the *Data quality evaluation* phase, we evaluate whether these requirements are fulfilled (step 9, Fig. 1) and, if not, whether resources allow for further investigation (step 11, Fig. 1). A subsequent round of data collection can then be necessary to improve data quality. For parameters with an indicator score of 5 for one or more countries in at least one variability category, or for parameters that are not geographically correlated and only classified into the technological variability categories, a sensitivity analysis is recommended to evaluate the impact of the high uncertainty on the results (step 12, Fig. 1).

Application to the paper recycling regionalization tool

Three parameters have at least one country with an indicator score of 5 in at least one variability category in the tool (*Energy mix*, *Sludge treatment technology mix* and *Other solid waste treatment technology mix*), and two are not geographically correlated (*Virgin material input* and *Substitution ratio*) (see supplementary information S3). The biomass fraction of total energy use is varied between 0 % and 96 % for the *Energy mix* parameter, which represents respectively the lowest and the highest national values in the International Energy Agency (IEA) database for the pulp and paper production sector. The sludge treatments to test are incineration, landfilling, landfarming and filler application (for example in cement or carboard industries) for all countries with an indicator score of 5 for the *Sludge treatment technology mix* parameter. The other solid waste treatments to test in a sensitivity analysis are incineration, landfill and open dumping for all countries with an indicator score of 5. Substitution ratio is varied between 62 %, which is the lowest paper substitution ratio used in literature (Viau et al., 2020), and 100 %. Finally, the virgin material input fraction is varied between 0 % and 30 %, a value recommended by Wang et al. (2012) to obtain the same properties as the virgin product.

2.5 LCA paper recycling regionalization tool

The LCA tool was built in *Python* to perform the LCA of specified paper recycling systems. The user needs to specify input data concerning the studied recycling system in an *Excel* template. The input data are: the recycled paper grade (GP, NP or CC), the mean composition of the bale to recycle according to ten waste categories, the fraction of material sent to each recycling country and the transport types and distances between the exporting and importing countries. The user can also improve the data quality of the model by adding data collected at steps 5 and 7 of Fig. 1 in the template.

From these input data, the tool computes the regionalized LCA impacts of the studied paper recycling system with the impact characterization method specified by the user, using the *ecoinvent* 3.7.1 version for background processes. This tool is available in the *Gitlab* repository cited in the Reference list (Provost-Savard, 2022b).

The list of activities used to create the tool is available in supplementary information S5. Most *ecoinvent* activities are only available for a few geographical locations, and RoW or *global* locations were selected for most processes. The regionalization performed in this article focuses on quantitative values of process parameters, and regionalization of pre-built background *ecoinvent* processes is out of the scope of this research. Because of the absence of a paper sludge incineration process in the *ecoinvent* database, a process was created using the method from Deviatkin et al. (2016). Transfer coefficients based on paper sludge composition were deduced from the *ecoinvent* paper incineration process, and emissions were calculated based on the deinking sludge composition from Abdullah et al. (2015) (see supplementary information S6).

3. Results

3.1 Application of the tool for the global regionalization of recycling life-cycle impacts on climate change

In this section, we use the paper recycling regionalization tool to study the influence of regionalizing life-cycle impacts on the carbon footprint of paper recycling processes. The regionalization results for the local recycling of 1 kg of wastepaper in every paper-recycling country for the *Climate change* impact category are presented in Fig. 5 (numerical results are available in supplementary information S7 (Provost-Savard, 2022a)). The bale composition was retrieved from the guidelines of the Institute of Scrap Recycling Industries (ISRI) for the Mixed Papers (54) category. This composition corresponds to 95 % of targeted papers, 2 % of untargeted papers and 3 % of other rejected materials (ISRI, 2020). We compare local recycling processes in this application, and therefore transport from sorting to recycling facilities is considered negligible. We excluded substitution modeling in this analysis in order to compare only the positive impacts of local recycling processes, and to allow a fair comparison between the countries, without using a substituted non-regionalized process from *ecoinvent* assuming technologically advanced primary productions.

Results range from 0.36 to 2.25 kg CO2-Eq/kg of wastepaper recycled for GP production, from 0.27 to 1.84 kg CO2-Eq/kg of wastepaper recycled for NP production and from 0.28 to 1.68 kg CO2-Eq/kg of wastepaper recycled for CC production. These results were compared to the results of existing wastepaper recycling LCA studies, excluding the sorting of paper from other commingled materials and the substitution steps. Some studies included the collection step, contrary to the present study, but this life-cycle phase was shown to have negligible impacts on the kg CO2-Eq emitted during the paper recycling process (Hong & Li, 2012; Wang et al, 2012). The results of the studies are all within the ranges obtained with the regionalization tool: between 0.5 and 1.5 kg CO2-Eq/kg of wastepaper recycled for five recycled paper grades and reprocessing technologies in Denmark (Merrild et al., 2008), 0.6 kg CO2- Eq/kg of wastepaper recycled to high grade printing and writing paper in China (Hong & Li, 2012), around 1 kg CO2-Eq/kg wastepaper recycled to newspaper in Finland (Dahlbo et al., 2005a), approximately 1 to 1.5 kg CO2-Eq/kg of wastepaper recycled for eight recycled paper grades in the United Kingdom (Wang et al., 2012) and approximately 0.5 to 0.6 kg CO2-Eq/kg of wastepaper recycled for eight paper grades in Italy (Arena et al., 2004). Generally, for all paper grades, North American and European countries have the best environmental performances, due to higher efficiency processes, cleaner energy and electricity productions and cleaner sludge and solid waste management practices. The contrast between developed and developing countries is observable for all paper grades, but is more significant for GP and NP production.

It is important to keep in mind that the regionalized climate change results are part of an effort to improve data quality, but are still based on many hypotheses and remain highly uncertain. Hence, these CO2-Eq emission values should not be used directly without contextualisation.

3.2 Application of the tool to Quebec's mixed paper recycling system

In this section, the tool is used to assess the environmental impacts of the global recycling system of the mixed wastepaper produced in the province of Quebec, in Canada. The bale composition assumed is the average composition of mixed paper bales exiting Quebec's sorting centers characterized from 2018 to 2020 by RECYC-QU´EBEC. These mixed paper bales are composed by 75 % of targeted papers, 10 % of plastics, 4 % of untargeted paper, 2 % of metals, 1 % of glass and 8 % of other materials (RECYC-QU´EBEC, 2020). From the 188 000 tons of residual mixed papers exiting Quebec's sorting centers yearly, only 10 % are recycled in the province (RECYC-QU´EBEC, 2021). The international destinations of the bales were estimated from data provided in the Canadian International Merchandise Trade Database (Statistics Canada, 2020). About 52 % of recovered papers generated in Quebec are recycled in India and 23 % in the United States. The remaining 15 % is sent to 34 different countries, the largest fractions going to China (3,18 %), Germany (3,18 %), South Korea (2,24 %), Pakistan (2,07 %), Viet Nam (1,79 %), Italy (1,18 %) and 28 others (totalling 1,36 %) (see supplementary information S8 (Provost-

Savard, 2022a)). The objective of assessing the regionalized environmental impacts of Quebec's mixed paper recycling system is to characterize the importance of regionalization regarding the life-cycle performance of recycling strategies of fibre exporting countries.

3.2.1 Scenario analysis

This section presents the results of four scenarios, which were used to evaluate the influence of regionalization on the LCA results of Quebec's global mixed paper recycling system. First, the results from the 100 % recycled GP production process with a RoW geography available in *ecoinvent* (*Ecoinvent global process)* are compared to the regionalized LCA results (*Regionalized case*). The third scenario corresponds to the local recycling of 100 % of mixed paper produced in Quebec (*100 % local recycling*). Finally, a scenario where 100 % of mixed paper produced in Quebec is landfilled (*100% landfill*) instead of recycled is tested to compare this waste management alternative to recycling.

Fig. 6 shows the normalized *ReCiPe* midpoint impact scores obtained from the *ecoinvent* process, the regionalized case, the local recycling case and the landfill case (numerical results are available in supplementary information S9 (Provost-Savard, 2022a)). While most impact scores are negative when using the *ecoinvent* process, meaning the impacts of the recycling process are more than compensated by the substitution of virgin resources, only nine impact categories remain negative when the recycling system is regionalized. Compared to the *100 % landfill* scenario, the *Regionalized case* presents higher potential impacts in some categories, indicating that recycling mixed paper from Quebec's sorting centers might prove worse for these impact categories than locally landfilling this paper without any valorization. The *100 % local recycling* scenario substantially diminishes the impact scores for most impact categories compared to the *Regionalized case*.

3.2.2 Sensitivity analysis

Results from the sensitivity analysis performed on the most uncertain parameters of the paper recycling regionalization tool described in section 2.4 are presented in supplementary information S10 (Provost- Savard, 2022a). From the sensitivity analysis, we conclude that the biomass share of total energy use doesn't have a significant impact on the results obtained. Sludge treatment processes also have a limited influence on the LCA results in most impact categories, and no conclusion is changed when this parameter is varied. However, sludge landfilling is clearly the worst treatment option in most impact categories. Other solid waste treatment processes don't change the conclusions for each impact category compared to the base regionalized case, except for the climate change category. For both substitution and virgin material input sensitivity analysis, all the environmental impacts respectively grow noticeably when the capacity of the recycled material to attain the same functionality as the virgin material substituted drops and when the quantity of virgin material used in the recycling process input is increased. These two parameters have the largest influence on LCA results and may reverse the conclusions for many impact categories.

4. Discussion, limitations of the study and future work

Two major conclusions can be deduced from the results. First, we need a collective effort to reduce uncertainties, increase the geographical representation and reduce the quantity of approximations of LCA studies. This can be achieved by sectorial parametrization efforts to create collaborative tools allowing to generate multiple case-specific scenarios efficiently. The available data in the literature concerning paper recycling process parameters are largely insufficient, leading to uncertain approximations. The methodology and the tool presented contribute to reduce uncertainties, but data availability remains a considerable problem in modeling the environmental impacts of recycling systems. Second, we observe that in developed countries, mostly North American and European countries, paper recycling seems to be performed with less impact on the environment. Hence, from a strictly environmental point of view, these countries should focus on improving local recycling structures, and aim to increase the fraction of paper recycled locally instead of exporting large quantities of wastepaper. However, economic and social constraints should also be studied to evaluate the sustainability of such objectives.

The access to regionalized data was a challenge in the construction of the tool. Some paper recycling process parameters are only available for a few countries, and the geographical estimation method leads to uncertain results. For example, the amounts of chemicals used in the recycled GP production process were only found for India, China and Denmark. The chemicals' use in the paper recycling process of all the other countries was estimated from these three data points. This method reduces the uncertainty compared to using exclusively the European process accessible in the *ecoinvent* database, but could be improved by the addition of new data points to the collaborative LCA tool. We invite all practitioners who possess regionalized data on paper recycling processes to contact us, as this precious data is useful to improve the accuracy of the LCA calculations of the tool. Our results showed that the substitution ratio is crucial in the representation of the environmental impacts of recycling processes, an idea already supported by many authors (Andreasi Bassi et al., 2017; Rigamonti et al., 2009). Nevertheless, our work did not include material quality modeling as an indicator of the amount of virgin material substituted by the recycled paper produced, or regionalization of substituted processes. This could be an interesting future research avenue and would contribute to refine the model developed in this study. Finally, the framework could be improved by refining the data quality evaluation assessment with a more comprehensive method than the pedigree matrix, for example using the framework proposed by Henriksen et al. (2021).

5. Conclusion

In this paper, we responded to the need to develop a parametrized and efficient method to regionalize data in LCAs of international recycling systems. This method guides LCA practitioners in the creation of parametrized tools in the recycling sector. The application of this framework allows to reduce the uncertainties linked to technologically and geographically dependent parameters, and to generate regionalized LCIs. A paper recycling regionalization tool that automatizes the choice of system boundaries and process parameters, as well as the estimation of missing data, was built based on the framework.

The methodology developed was used to assess the impacts on climate change for every paper recycling country and for three different paper grades, namely GP, NP and CC. Results indicate that developed countries with high efficiency paper recycling processes should focus on improving local recycling facilities' capacities, to avoid exporting these papers to countries with less environmentally efficient paper recycling systems.

A case study was performed on Quebec's mixed paper international recycling system. Mixed paper originating from Quebec's sorting centers is sent to 38 international destinations, mainly to India and to the United States. Compared to the *ecoinvent* 100 % recycled GP production *global* process, the regionalization performed with the developed methodology led to notable impact increases in most *ReCiPe* midpoint impact categories. The *100 % local recycling* scenario (compared to only 10 % in the base regionalized case) led to great environmental benefits. Hence the results indicate that priority strategies to reduce environmental impacts should be improving paper bales' quality and developing local recycling markets.

This research provides insights related to LCI regionalization and semi-automated generation as a means to efficiently incorporate data of various granularity and specificity, in order to estimate geographic variations and ultimately reduce uncertainties. Future research should address recycled material quality and virgin material substitution modeling, as substitution potential constitutes one of the most uncertain parameters in recycling LCAs.

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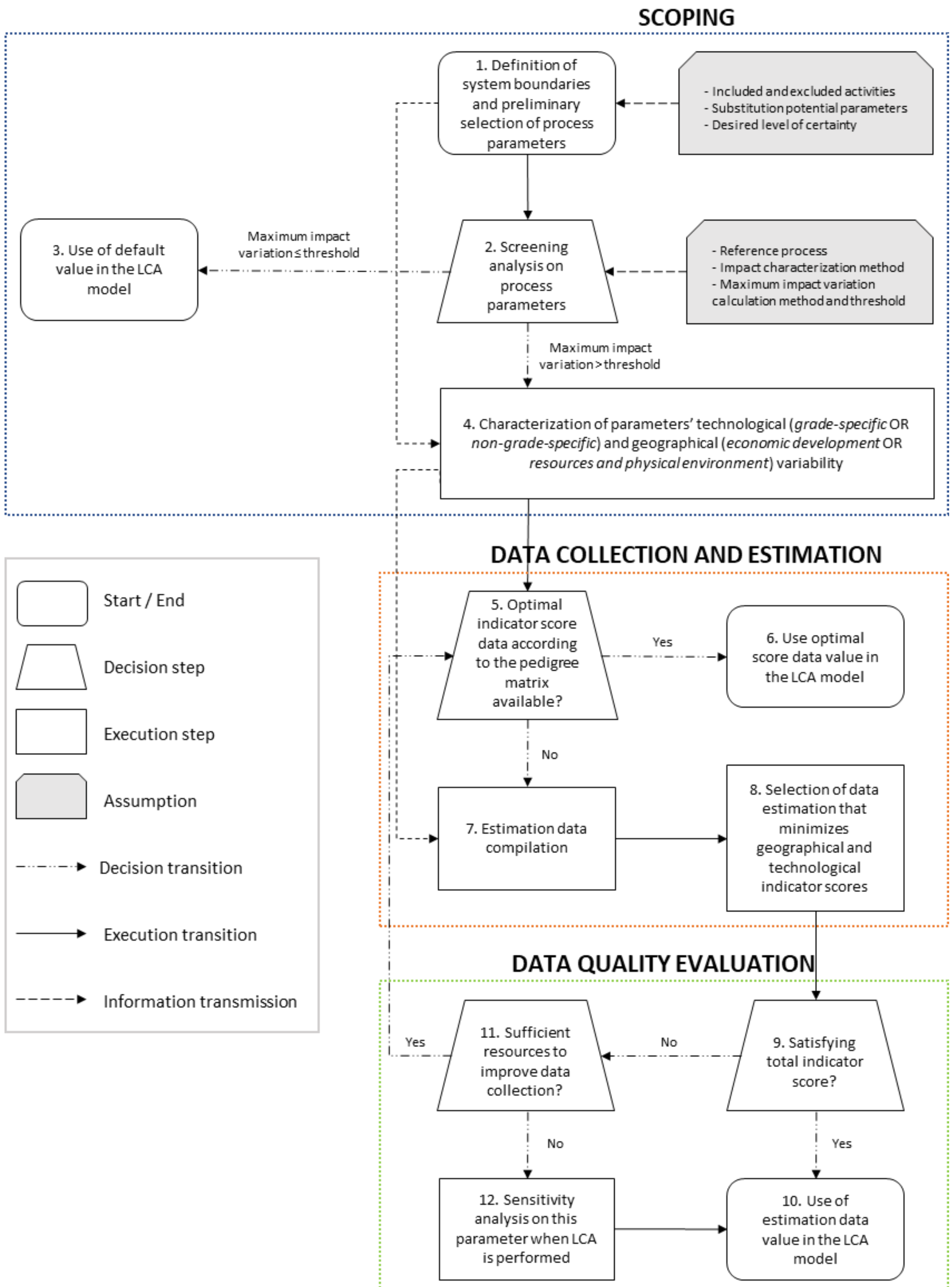

Figure 1: Methodological framework to guide the parametrization and systematization of the generation of life-cycle inventories for the recycling of different material types

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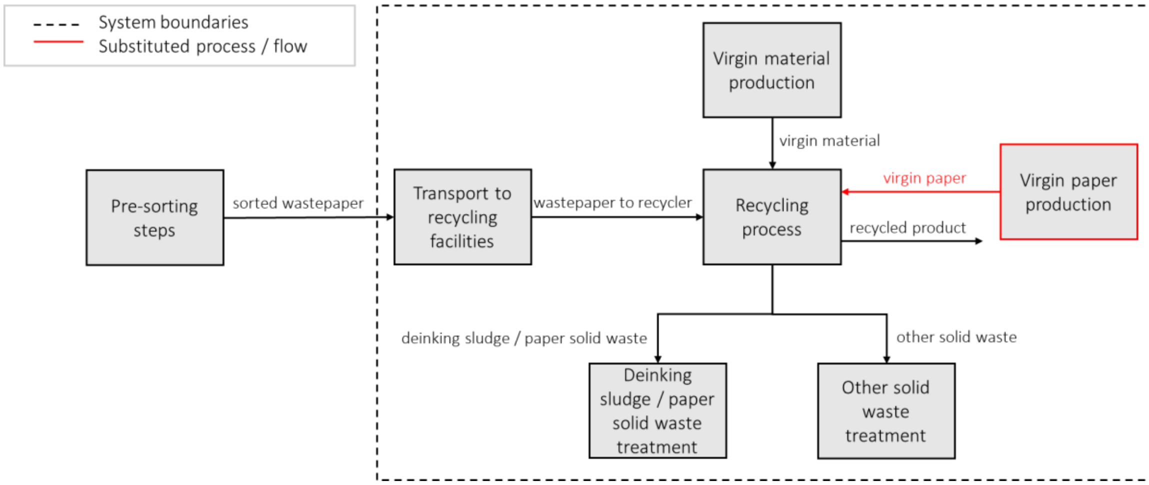

Figure 2: Included and excluded activities in the LCA paper recycling regionalization tool

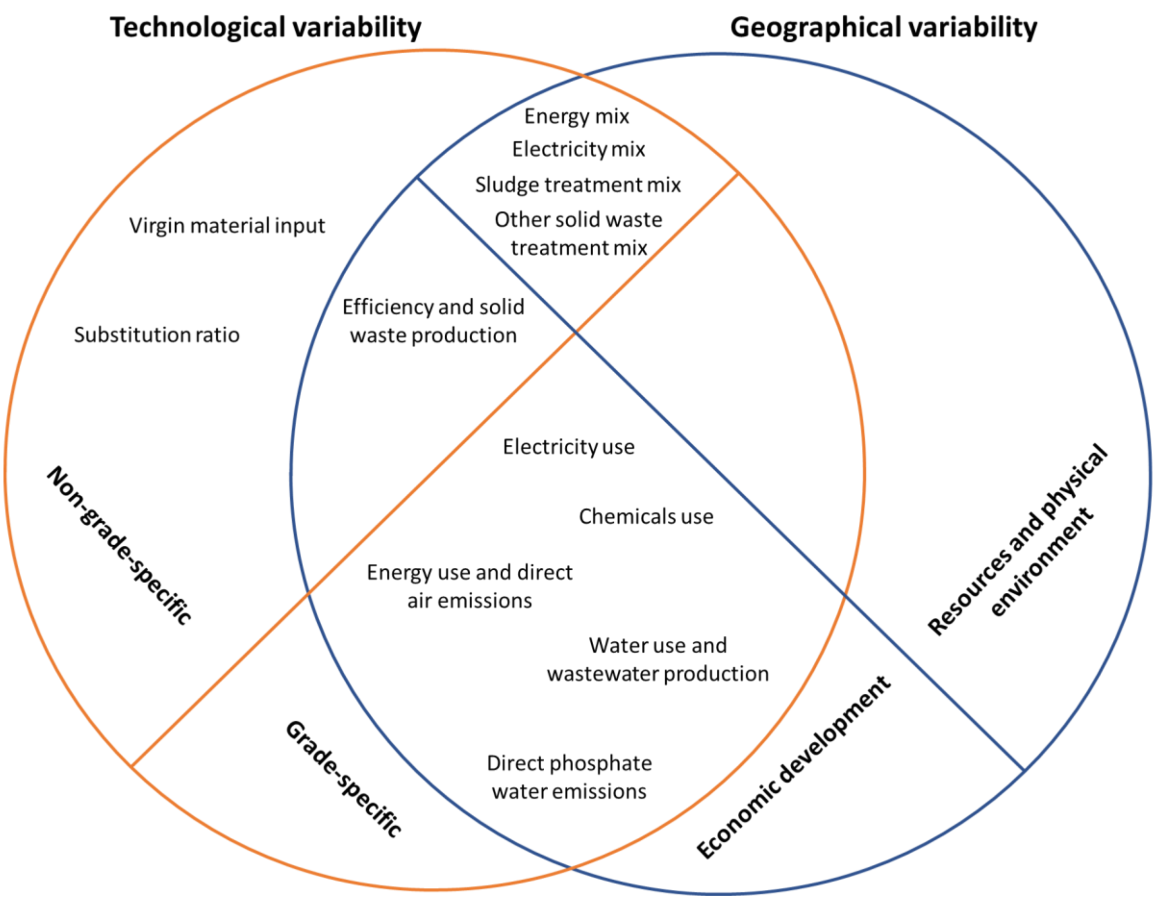

Figure 3: Classification of the paper recycling regionalization tool process parameters into the two technological variability categories (non-grade-specific parameters and grade-specific parameters) and the two geographical variability categories (parameters linked to economic development and parameters linked to available resources and physical environment)

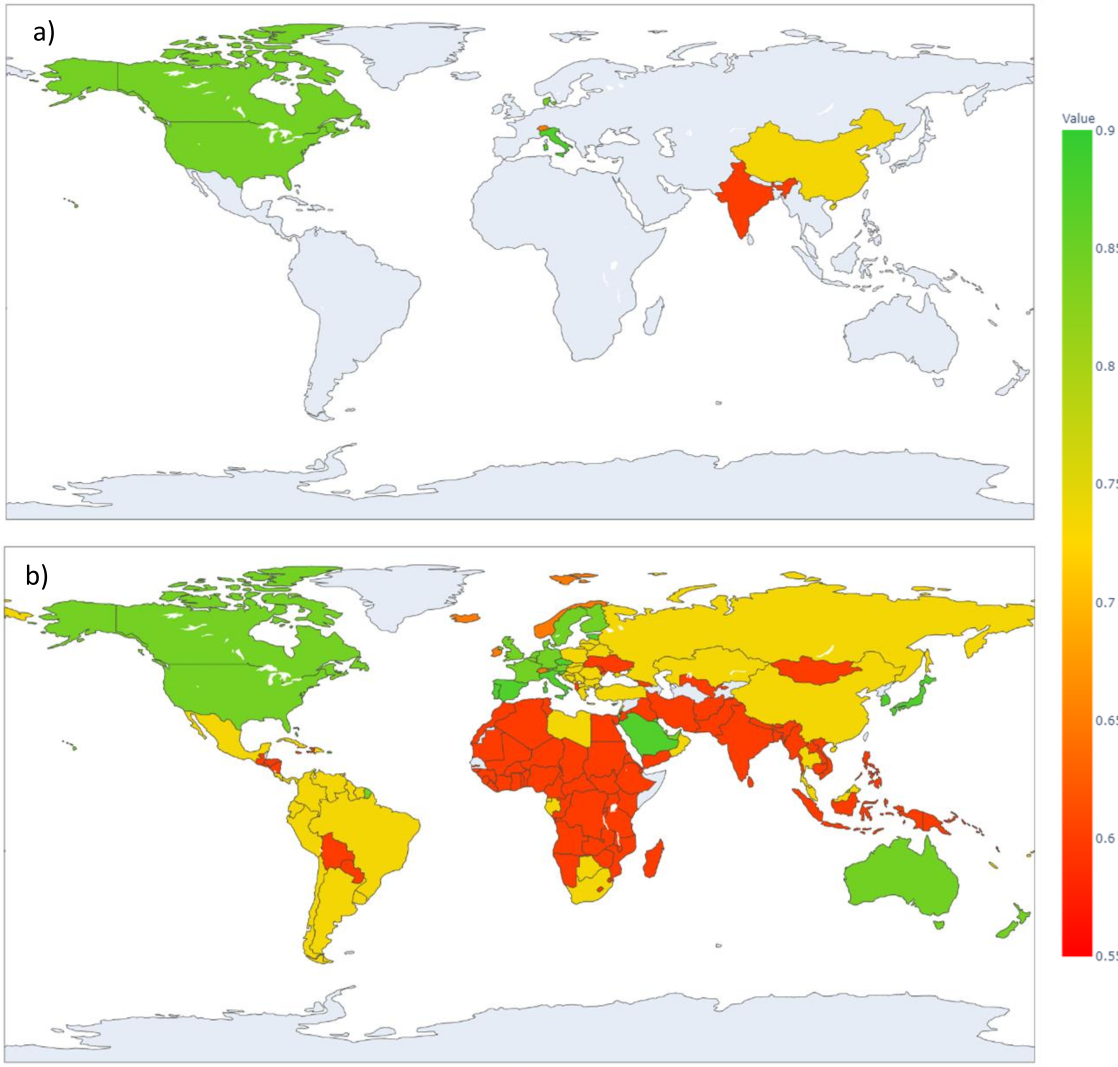

Figure 4: Regionalization results for the *Efficiency* process parameter a) Level 1 and 2 geographical indicator score countries according to the pedigree matrix for wastepaper recycling efficiency b) Estimation of wastepaper recycling efficiency for all countries with a paper recycling system

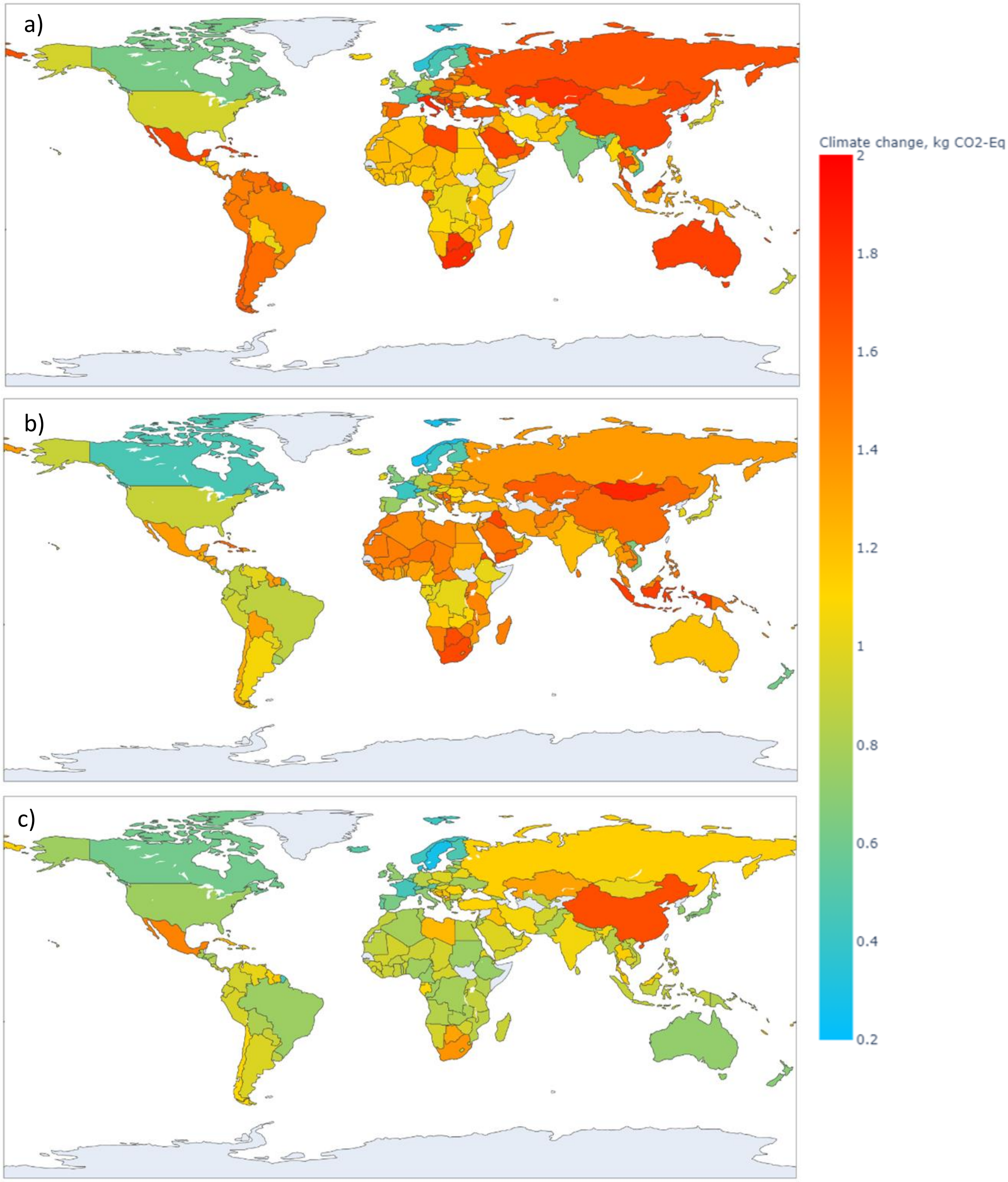

Figure 5: Impact on climate change (kg CO_2-Eq) of recycling 1 kg of wastepaper per country a) Graphic paper production b) Newsprint production c) Corrugated cardboard production

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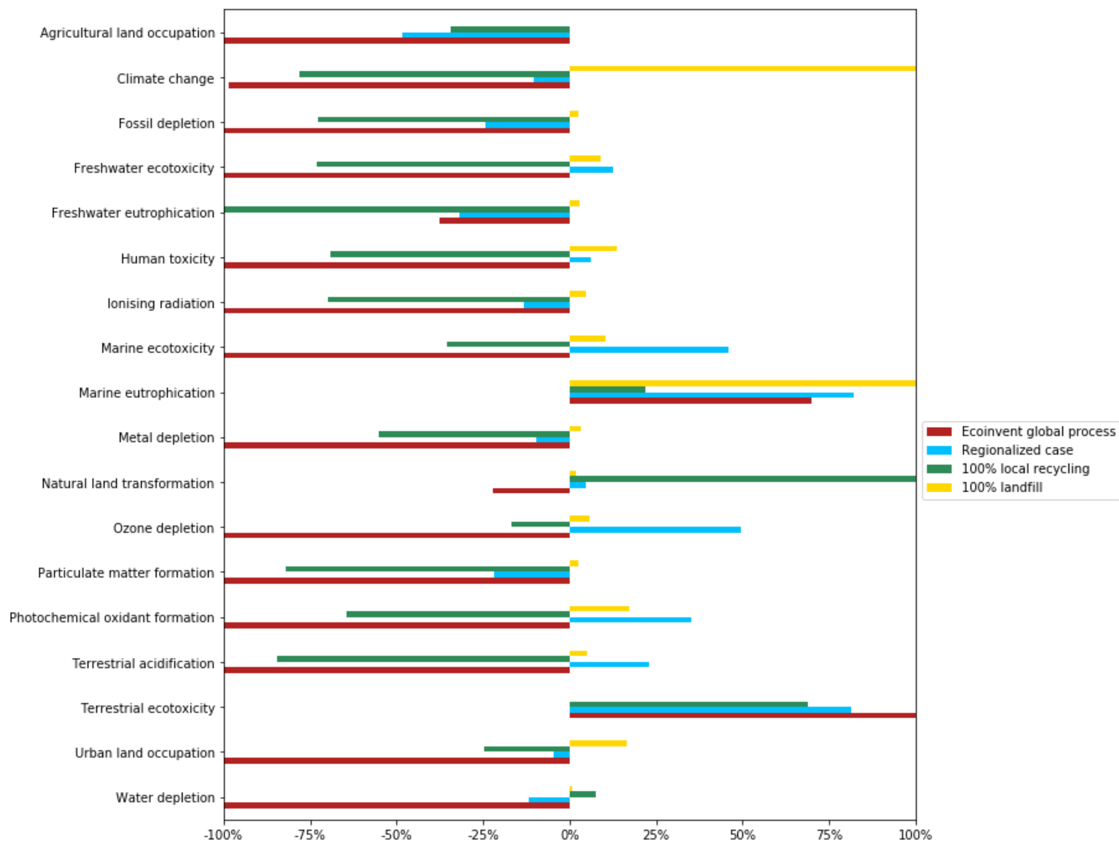

Figure 6: Normalized scenario analysis results on 18 ReCiPe midpoint impact categories for the recycling of 1 kg of wastepaper from Quebec's sorting centers

Table 1: Pedigree matrix indicator scores descriptions (from Weidema, 2013) and examples of each indicator score category for geographical and technological correlation linked to paper recycling processes

Indicator score		1	2	3	4	5
Geographical correlation	**Description**	**Data from country under study**	**Average data from larger area in which the area under study is included**	**Data from area with similar production condition**	**Data from area with slightly similar production conditions**	**Data from unknown or distinctly different area**
	Examples	*Economic development:* Representative national average or proxy sampling *Resources and physical environment:* Representative national average or proxy sampling	*Economic development:* Average data from 5 or less countries in same geographic area *Resources and physical environment:* Average data from 5 or less countries in same geographic area	*Economic development:* Data from country with similar GDP/capita *Resources and physical environment:* Data from country with similar resources / infrastructures	*Economic development:* Data from country with slightly similar GDP /capita for parameters that depend on economic development *Resources and physical environment:* Data from country with slightly similar resources / infrastructures	*Economic development:* Continental average, global average, other country's national average or proxy sampling *Resources and physical environment:* Continental average, global average, other country's national average or proxy sampling
Technological correlation	**Description**	**Data from enterprises, processes and materials under study**	**Data from processes and materials under study**	**Data from processes and materials under study but from different technology**	**Data on related processes or materials**	**Data on related processes on laboratory scale or from different technology**
	Examples	*Non-grade-specific:* Data from paper recycling process *Grade-specific:* Data from specific product grade recycling process		*Non-grade-specific:* *Not applicable* *Grade-specific:* Data from paper recycling process	*Non-grade-specific:* Data from virgin paper production processes *Grade-specific:* Data from virgin paper production processes	*Non-grade-specific:* Average data from recycling processes or average data from industries *Grade-specific:* Average data from recycling processes or average data from industries