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RESEARCH ARTICLE

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Opening the black box of the use phase in circular economy life cycle assessments

Environmental performance of shell jacket reuse

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Abstract

Life cycle assessment (LCA) is highly needed and widely used to assess the environmental performance of circular economy (CE) measures such as reusing and sharing. However, the results of such LCAs are hampered by limited knowledge about the use phase of consumer products and oversimplification of important use phase aspects such as product functionality, user behavior, displacement, and rebound effects. This paper aims to validate the usefulness of a framework designed to assist practitioners in the generation and utilization of such knowledge in LCAs of circular measures. To validate the framework, a case study is used: reuse of shell jackets enabled by "premium secondhand" stores for outdoor equipment and clothing. The paper demonstrates that conclusions about the environmental performance of reuse can easily be altered depending on the functional unit definition, whether real user behavior data are used, and whether imperfect displacement and rebound effects are considered. For instance, shell jacket life cycles that include reuse and thus may be labeled "circular" have significantly higher environmental impact per use occasion than "linear" ones (used by one principal user the entire lifespan), since "circular" shell jackets are used less frequently, in particular during their first use span. Through facilitating the generation and utilization of environmentally relevant use phase data, which are otherwise often overlooked, the framework seems capable of supporting a better understanding of the environmental performance of CE measures.

KEYWORDS
consumer behavior, functional unit, industrial ecology, life cycle inventory (LCI), rebound effects, secondhand markets

1 | INTRODUCTION

The vision of a circular economy (CE) promotes measures such as reusing, repairing, and sharing, under the assumption that it leads to reduced environmental impact of consumer products (Blomsma & Brennan, 2017; Boulding, 1966). However, CE measures may result in burden-shifting between life cycle stages or environmental impact categories (Böckin, Willskytt et al., 2020; Harris et al., 2021; van Loon et al., 2021). Therefore, whether CE measures reduce environmental impact as intended needs to be investigated from a life cycle perspective on a case-by-case basis. To this end, life cycle assessment (LCA) is commonly deployed.

However, the lack of consideration of, and knowledge of, important aspects of the use phase of consumer products has been argued to limit the accuracy of state-of-the-art (SoA) LCAs of CE measures (hereafter CE LCAs) (Harris et al., 2021; Zink & Geyer, 2017). Such use phase aspects relate to: products, for instance, how functionality is defined and modeled (Kjaer et al., 2016); users, for instance, about their behavior in terms of frequency of product use (Harris et al., 2021); system-level effects of CE measures on products and users, for instance, rebound effects arising if circular products do not displace production of new ones, or if they allow users to save money which can be re-spent on other consumption (Castro et al., 2022; Zink & Geyer, 2017). Inadequate consideration of such use phase aspects could imply that the potential environmental benefits of CE measures are overestimated or that LCAs fail to identify cases where CE measures increase environmental impacts (Makov & Font Vivanco, 2018; Siderius & Poldner, 2021; Zink & Geyer, 2017).

To address these limitations of SoA CE LCAs, a framework was developed to guide practitioners in mapping CE use phases more systematically and comprehensively and in utilizing the mapping in the goal and scope and life cycle inventory (LCI) of CE LCAs (André & Björklund, 2022, 2023). The usefulness of the framework was tested in a case study focusing on the reuse of shell jackets enabled by "premium secondhand" outdoor stores in Sweden. The specific case study was chosen, inter alia, because it was hypothesized to include user groups with distinct characteristics and behaviors. This, in turn, was hypothesized to be conducive to testing the mentioned use phase aspects of the framework. The comprehensive mapping of the case study, presented in a previous paper (André & Björklund, 2023), revealed insights about the use phase that could have a significant impact on LCA results. For instance, it was found that shell jacket lifespans were similar in the "circular" and "linear" scenarios and that shell jackets in the "linear" scenario were used more frequently and hence for a higher number of total use occasions.

To further test the usefulness of the framework, this paper seeks to demonstrate, first, how the mapping can be utilized in the goal and scope and LCI of a CE LCA and, in turn, how this may influence CE LCA results. The results of this CE LCA are compared to how the results might look when deploying assumptions and modeling choices that are common in SoA CE LCAs. In addition, the paper demonstrates how the mapping allows for different methodological choices and modeling approaches and how these may influence results. The ultimate purpose of the framework, and by extension this paper, is to contribute to a deeper and more nuanced understanding of the real environmental performance of CE measures.

2 | METHODS

The first part of this section describes the case study used to test the usefulness of the framework (Section 2.1). Thereafter, the logic of the framework is described (Section 2.2) while simultaneously summarizing the most important results of the comprehensive mapping of the case study (André & Björklund, 2023).

2.1 | Case study

The case study focuses on the reuse enabled by two "premium secondhand" outdoor stores in Sweden that sell used clothing and equipment for sport and outdoor recreational activities, for example, backpacks, skis, and shell jackets. The "premium" refers to their focus on high-quality products. Products are handed in by previous users who, upon secondhand resale, receive half of the secondhand sales price while half is retained by the stores.

This case study was chosen for a number of reasons:

- Users of outdoor equipment, such as shell jackets, were assumed to have distinct user characteristics in terms of behavior and preferences. Studying the influence of such user characteristics on LCA results was hypothesized to be conducive to testing the usefulness of the framework.
- Shell jackets in particular were deemed a suitable product to represent the reuse enabled by the studied secondhand stores, inter alia, because they are among their most frequently sold product types. (Personal communication, K. Olivensjö, July 26, 2021; A. Mangs Bergmark, August 24, 2021.)
- In addition, performance-related product properties of shell jackets, for instance, water repellency, could be measured quantitatively by collaborating researchers (André & Swenne, 2023) and used to inform framework aspects such as functionality and displacement (Vadenbo et al., 2017; Zink & Geyer, 2017).
- Reuse of outdoor equipment to a large extent takes place locally in Sweden (while many other product types are mainly reused abroad) which facilitates comprehensive data collection about the most relevant parts of the use phase.

A variety of comparisons will be made throughout the article. In general, they all compare:

- Shell jacket life cycles that include reuse enabled by a resale at the secondhand stores. This alternative is referred to as the two-user (2U) life cycle. The first users, the sellers, are referred to as 2U1 users and the second users, the buyers, are referred to as 2U2 users.

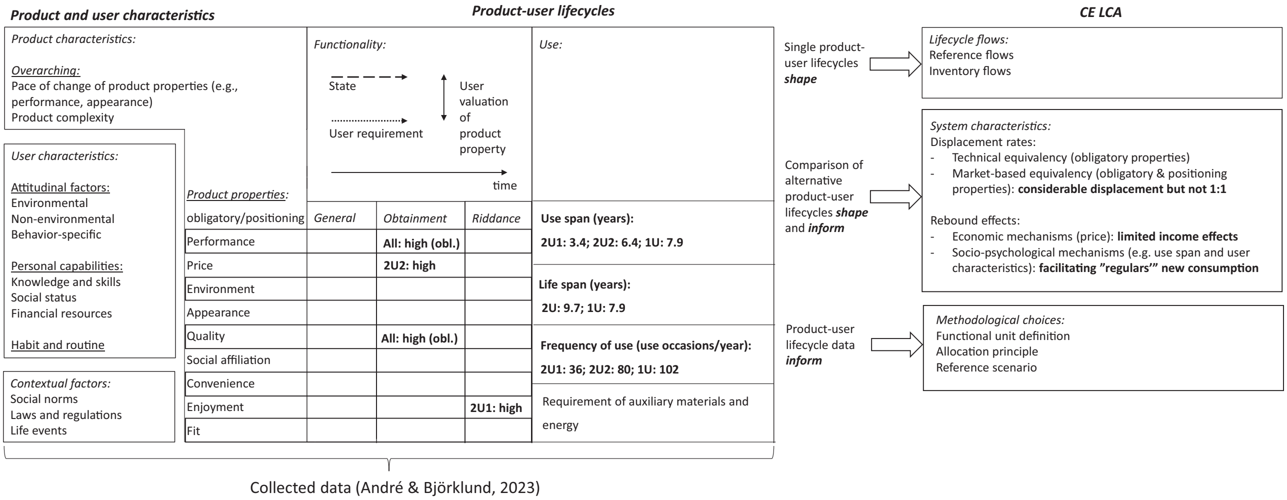

FIGURE 1 Mapping of potentially influential use phase aspects (in bold) for the environmental performance of reuse (André & Björklund, 2023) used as a foundation for the circular economy life cycle assessment (CE LCA; this paper). *Source*: Figure adapted from André and Björklund (2023).

- Reference scenarios where shell jackets are used by one principal user for the entire lifespan, based on data collection at five conventional (i.e., selling new products) stores for outdoor clothing and equipment. This alternative is referred to as the one-user (1U) life cycle.

The LCI for the production of shell jackets was based on Goffetti et al. (2022). Data for the comprehensive mapping of the use phase of the case study were collected through both user surveys and interviews with store managers. The reader is referred to André & Björklund (2023) for further background information on the case study and to the Supporting Information (S1) for more information on the CE LCA, for example, system boundaries and assumptions.

2.2 | Description of framework and mapping of the product–user life cycles of the case study

In this section, the logic of the framework is described, largely by summarizing the most important results of the comprehensive mapping of the case study (Figure 1) (André & Björklund, 2023). In addition to describing the framework, this serves the purpose of acquainting the reader with these results[1], which in the results section of this article will be used as input to the modeling of the CE LCA of the case study (Section 3) and thus, form the foundation for the results of the CE LCA of the case study (Section 4).

Figure 1 illustrates that the ultimate utility of collecting data following the framework is to *shape* and *inform* aspects of *CE LCA* (the right column). The collected data describe *product–user life cycles* (the two center columns). The term *product–user life cycle* accentuates that life cycles studied in CE LCAs are the results of interplays between both product characteristics, such as design, and user characteristics, such as attitudes (the left column, involving largely qualitative data useful for understanding why product–user life cycles look the way they do). Product–user life cycles are composed of *functionality* (left center column) and *use* (right center column).

The first component of product–user life cycles, *functionality*, is described in terms of *states* of, and *user requirements* on, *product properties*, for example, performance, appearance, enjoyment, and environment. Functionality data may inform the choice of *functional unit definition* and shape *reference flows* (e.g., amount of jackets produced and reused required to fulfill a functional unit). Functionality data may also give insight into motivations for *riddance* and *obtainment*. For instance, if the state of a product property declines so that it no longer fulfills the user's requirement on the property it could prompt riddance, and if the state matches the requirements of a new user, it could prompt obtainment.

User requirements on product properties of shell jackets were, for the most part, similar among the three user groups 1U, 2U1, and 2U2 (André & Björklund, 2023). Essentially, all users considered *performance* and *quality* to be "very important" when buying shell jackets (that is, at *obtainment*). Some 2U1 users' *riddance* decisions seemed to be largely motivated by the *enjoyment* of purchasing new shell jackets. 2U2 users' obtainments of secondhand shell jackets seemed to be mainly motivated by the *price* and also the *environment*. As regards the *states* of product properties, the condition of shell jackets was judged by users as around 0.73 on a 1–0 scale (where 1 = new; 0.8 = excellent; 0.6 = good; 0.4 = decent; 0.2 = poor) at the time of secondhand resale. (André & Björklund, 2023)

The second component of product–user life cycles, *use* (right center column), is composed of the aspects: *use span*, *lifespan*, *frequency of use*, and *requirement of auxiliary materials and energy*. In this case, some important similarities and differences in terms of product *use* between the studied product–user life cycles were (André & Björklund, 2023):

- The total *lifespan* is slightly longer in the 2U life cycle than the 1U life cycle: 9—10 years (2U1 is on average 3—4 years) compared to 7—8 years.
- Due to a higher *frequency of use*, shell jackets in the 1U life cycle are used more than in the 2U life cycle: around 800 and 625 use occasions, respectively. 1U users reportedly use their shell jackets on 102 occasions per year, while 2U1 and 2U2 users use theirs 33 and 80 times per year, respectively.

This implies that the main difference between the life cycles is that the principal use of shell jackets is delayed in the 2U life cycle, for the duration of the first use span. An explanation for the comparatively low frequency of use among 2U1 users is that frequency of use is likely connected to the riddance decision, that is, their user requirements have not been fulfilled for some reason. With this in mind, the low frequency of use during the first use span was a surprising, yet, reasonable finding (André & Björklund, 2023).

Further, the *system characteristics*, *displacement rates*, and *rebound effects* (right column) are shaped and informed by comparisons of alternative product–user life cycles, in terms of, for instance, *price*. By inventorying *user characteristics* and *price* throughout life cycles, it was found that income effects and thus economic rebound effects are probably rather limited: for 2U1 users, because the practice of buying new and selling secondhand shell jackets is rather costly, and for 2U2 users, because a large share would not have bought shell jackets from the same high-quality brands unless they could be found at discounted prices secondhand, but instead spent the same amount of money on new lower-quality shell jackets. On the other hand, the mapping found evidence to suggest that the existence of secondhand stores could contribute to intensifying consumption for some 2U1 users, as theorized by Fox (1957) and others (for example, Cooper & Gutowski (2017); van Loon et al. (2021)). These users were referred to as "regulars" since they frequently sell rather "new, nice and expensive gear" (personal communication, A. Mangs Bergmark, August 24, 2021) at the secondhand stores. Displacement rates represent the extent to which a circular product displaces the need for production of new products which would have been required unless the circular product was obtained. In this case, many, but not all, secondhand obtainments seemed to occur instead of new product obtainments (André & Björklund, 2023).

3 | SCENARIOS AND MODELING CHOICES

The following sections (Sections 3.1–3.4) motivate the analyzed scenarios and modeling choices included in the paper, for functional unit definition, reference scenarios, displacement rates, and rebound effects. Most importantly, it is explained how using the framework mapping may shape environmentally relevant flows and inform methodological choices and modeling approaches of CE LCAs: first, in general terms and then, in this specific case study.

The approach to test the usefulness of the framework in terms of its quantitative implications for CE LCA results consists of the following parts:

- A hypothetical CE LCA of the case study representing typical choices made and scenarios explored in SoA CE LCAs, referred to as the SoA-LCA.
- A CE LCA of the case study using the framework mapping, referred to as the framework F-LCA. The F-LCA in turn consists of:
- a baseline version, referred to as the BF-LCA (for baseline framework), designed to be compared to the SoA-LCA. To exemplify how using the framework to conduct CE LCAs may influence results and interpretations of the environmental performance of CE measures, the environmental results of the BF-LCA are compared to the results of the SoA-LCA;
- a sensitivity analysis of choices and scenarios in terms of functional unit definition, reference scenarios, displacement rates, and rebound effects based on findings of the framework mapping. The purpose of the sensitivity analysis is to demonstrate how methodological choices and modeling approaches may influence the results of CE LCAs.

The SoA and BF LCAs include choices and scenarios on functional unit definition, reference scenarios, and displacement rates while the sensitivity analysis, in addition, includes scenarios of rebound effects.

3.1 | Functional unit definition

Functional unit definitions in LCA shall specify what functions products deliver, how much, for how long and how well, and, to the extent possible, how functionality (i.e., how well) changes over time. What functions products deliver, how well, and whether alternative products are comparable are often largely subjective matters (Kjaer et al., 2016). Therefore, data on *user requirements on product properties* can be useful information for defining functional unit definitions.

Functional unit definitions are recommended to be based on quantitative measures of properties related to the principal functions of products (ISO 14044, 2006). Such properties may be referred to as *obligatory* (Weidema et al., 2004), in other words, properties that products must have to be considered viable alternatives in comparative LCAs, such as CE LCAs. There are also *positioning properties* that are not obligatory but influence the market position of products (Weidema et al., 2004). When positioning properties differ notably between alternatives, it is recommended to

TABLE 1 Overview of the functional unit definitions in the state-of-the-art (SoA) and BF life cycle assessments (LCAs) and the sensitivity analysis.

SoA-LCA and BF-LCA	FU1	1 year's use of a shell jacket that is trusted to not break and to keep its user comfortably warm and dry
Sensitivity analysis of F-LCA	FU1a	a. constant functionality over time
	FU1b	b. functionality deteriorates over time
	FU2	100 use occasions during which a shell jacket is trusted not to break and to keep its user comfortably warm and dry
	FU2a	a. constant functionality over time
	FU2b	b. functionality deteriorates over time

include them in the functional unit or, at least, explicitly acknowledge them (Goedkoop et al., 1999; Kjaer et al., 2016; Weidema et al., 2004). In this case study, because performance (e.g., water repellency) and quality (e.g., trusted to not break) were consistently regarded as "very important" by all user groups (André & Björklund, 2023), these properties were deemed obligatory and appropriate to include in functional unit definitions. Small variances in positioning properties were noted (André & Björklund, 2023) but deemed insignificant to the comparison.

For choosing the temporal reference (*how long*) of the functional unit definition, it is relevant that the use phase of clothing is hard to define: does clothing deliver its functions while merely being an active part of a user's wardrobe or only when, in fact, worn (Klepp et al., 2020)? 1U and 2U life cycles may differ for more aspects than lifespan and the empirical observation that there is considerable variability in terms of frequency of use (André & Björklund, 2023) motivates exploring functional unit (FU) definitions based on two types of temporal references (Table 1). The first, FU1, is defined as one year's use of a shell jacket that is trusted to not break (because *quality* was an obligatory property) and to keep its user comfortably warm and dry during outdoor activity (because *performance* was an obligatory property). "One year's use" refers to the time during which a jacket is an active part of a user's wardrobe (Klepp et al., 2020). This functional unit captures a key feature of reuse, namely use extension, and is commonly applied in CE LCAs of measures based on use extension (Böckin, Willskytt et al., 2020). Hence, it was the chosen functional unit for the BF and SoA LCAs. The second, FU2, which is part of the sensitivity analysis, is defined as 100 use occasions during which a shell jacket is trusted not to break and to keep its user comfortably warm and dry. FU2 captures the variability in frequency of use between users. Ultimately, it is during actual use occasions that shell jackets are meant to deliver the highly valued properties of performance and quality. In addition, this FU is relevant since the frequency of use can be expected to influence the rate of functionality deterioration for shell jackets and other similar products.

Both FU1 and FU2 are limited in the sense that they implicitly assume that the functionality is constant, although it does decrease over time (André & Swenne, 2023). To the extent possible, functionality deterioration over time shall be accounted for (ISO 14044, 2006). Accordingly, two versions of FU1 and FU2 are explored (Table 1): (a) where functionality is constant and (b) where functionality deterioration is accounted for[2]. In the latter version, the function delivered by each shell jacket is quantified as the integral of a function of functionality over time or use occasions. These functional unit definitions (FU1b and FU2b) capture that shell jackets deliver more function per year or use occasion (i.e., how well) in the beginning than toward the end of their life cycles. Thus, they could reduce the risk of overestimating the environmental benefits of circular product life cycles, by giving less credit to later parts of life cycles where functionality may be low.

3.2 | Reference scenario

CE LCA results are highly sensitive to the reference scenario, often representing more linear life cycles, to which circular life cycles are compared (Kjaer et al., 2016). In this case, the 1U life cycle serves as the reference scenario. In the BF-LCA, the reference scenario represents real users who buy new shell jackets at conventional stores and use them for the majority of their lifespans. The comprehensive mapping established that shell jackets in the 1U life cycle are used more frequently and for almost as long as those of the 2U life cycle (Figure 1; Table 2). This real reference scenario seems to represent a fairly ideal life cycle in terms of approaching the maximum technical lifespan of current shell jackets (see Section 5). Therefore, in the sensitivity analysis, alternative hypothetical reference scenarios are explored, in which the shell jackets of the 2U life cycle would not be used further but instead be discarded (RS1), or used for 1 to 4 years longer by the same user (RS2–RS5) (Table 2).

The SoA-LCA represents common assumptions made in SoA CE LCAs. Such assumptions may be based on primary data collection, for example, from case study participants, but are commonly based on secondary data, whose validity in other contexts may be limited, or made arbitrarily (Polizzi di Sorrentino et al., 2016). Given that the (perceived)[3] main feature of reuse is use extension, data collection in reuse studies typically focuses on the use and lifespans of products (Böckin, Willskytt et al., 2020). For the SoA-LCA, the average first use span was estimated based on interviews with the store managers of the secondhand stores as around 4 years (personal communication, K. Olivensjö, July 26, 2021; A. Mangs Bergmark, August 24, 2021). A survey with shell jacket users and brands suggests that users' average intended use span was 5—6 years and the perceived lifespan

TABLE 2 Overview of scenarios compared in terms of use and lifespans (years) of each user group in the state-of-the-art (SoA) and BF life cycle assessments (LCAs) and the sensitivity analysis.

	Reference scenarios (RS) (years)	Alternative scenarios (years)		Source
User group	1U	2U1	2U2	
SoA-LCA	4	4	2.5	Assumptions based on interviews and literature (see text)
BF-LCA	7.9	3.4	6.4	User surveys (André & Björklund, 2023)
Sensitivity analysis of F-LCA	RS1: 3.4; RS2: 4.4; RS3: 5.4; RS4: 6.4; RS5: 7.4	3.4	6.4	Reference scenarios: hypothetical Alternative scenarios: user surveys (André & Björklund, 2023)

according to brands of their best-selling shell jackets was 7–8 years (European Outdoor Group, 2015). Based on this, the second use span enabled by secondhand stores is assumed to range between 1 and 4 years, and on average, 2.5 years. This could typically yield a SoA LCA between a 1U life cycle of around 4 years and a 2U life cycle of around 6.5 years.

3.3 | Displacement rates

How CE measures could reduce the environmental impacts of consumption is by supplying circular products that can be obtained instead of new ones and thus displace new production (Zink & Geyer, 2017). The purpose of *displacement rates* is to capture the degree to which circular products displace new production. Essentially, they capture the extent to which circular products fulfill the same function as new ones. There are two main approaches: *technical* and *market* equivalency (Vadenbo et al., 2017).

The technical equivalency approach (Vadenbo et al., 2017) aims to capture deterioration in *states* of quantifiable product properties that are regarded as *obligatory*, in this case, *performance (quality* is less quantifiable). To establish a displacement rate based on technical equivalency (DR_T), an average is used of four performance-related properties plotted over the course of shell jacket lifespans (in this case, weighted equally): water penetration resistance, water repellency, breathability, and air permeability (André & Swenne, 2023). Based on this average, secondhand shell jackets have 89% of their original functionality at the time of secondhand resale (3.4 years into the lifespan), yielding a displacement rate of 0.89.

Accounting for displacement using the market approach (Vadenbo et al., 2017; Zink et al., 2016) aims to capture the fact that circular products may not displace new products even if they were technically equivalent, because they may not compete in the same market. In other words, the market approach captures differences between products not only in terms of obligatory but also positioning properties. In this study, a market-based displacement rate (DR_M), is derived in two ways which both yield a value around 0.75: based on 2U2-users' statements on motivations for obtainment (see Supporting Information S1) similar to Castellani et al. (2015), Farrant et al. (2010), and Stevenson and Gmitrowicz (2012) and on users' assessments of product condition at the point of secondhand resale (based on the assumption that users include not only obligatory but also positioning properties, e.g., appearance in this assessment). In order not to overestimate the benefits of reuse by assuming perfect displacement, the market-based displacement rate is deployed in the BF (Table 3). The sensitivity analysis tests the influence of the technical equivalency approach as well as assuming perfect displacement (DR_P) as is common in SoA CE LCAs (Makov & Font Vivanco, 2018; Zink & Geyer, 2017) and thus used in the SoA-LCA (Table 3).

3.4 | Rebound effects

Environmental rebound effects of CE measures occur when "increases in production and consumption efficiency are offset by increases in production and consumption" (Zink & Geyer, 2017). Mostly, the literature on the rebound effects of CE measures has focused on economic mechanisms (Castro et al., 2022), for example, re-spending of income effects (since circular products are typically cheaper than new ones) on other consumption, but rebound effects may also be generated by socio-psychological mechanisms (Hofstetter et al., 2005). One example is moral licensing, which refers to when perceived environmental behavior in one instance justifies, to a user, less environmental behavior in another (Dütschke et al., 2018). The exact mechanisms behind rebound effects are difficult to establish, and several mechanisms could contribute in a synergetic manner to the same observed rebound effect (van den Bergh, 2010). Nonetheless, the framework distinguishes between economic and socio-psychological mechanisms because their identification and assessment may be informed by different types of data: the former largely by price and the latter by, for example, user characteristics, use span, and riddance motivations.

In this case, the assessment of rebound effects is informed primarily by the mapping of price data, indicative of economic rebound effects, and further supported by data on user characteristics ("regulars'" high valuation of enjoyment) indicative of socio-psychological mechanisms. Although

TABLE 3 Overview of displacement rate scenarios in the state-of-the-art (SoA) and BF life cycle assessments (LCAs) and the sensitivity analysis.

	Displacement approach	Displacement rate (DR)	Source	Functional unit
SoA-LCA	Assumption of perfect displacement by default	$DR_P = 1$	None	FU1a
BF-LCA	Market equivalency	$DR_M = 0.75$	Calculations based on user survey results: motivations for obtainment and product condition as assessed by users	FU1a, FU2a Not applicable to FU1b and FU2b because it would double-count the functionality deterioration (see Supporting Information S1)
Sensitivity analysis of F-LCA	Technical equivalency	$DR_T = 0.89$	Laboratory tests on four performance-related obligatory properties: water penetration resistance, water repellency, air permeability, and breathability	FU1a, FU2a Not applicable to FU1b and FU2b because it would double-count the functionality deterioration (see Supporting Information S1)
	Assumption of perfect displacement by default	$DR_P = 1$	None	FU1a, FU2a

TABLE 4 Overview of scenarios explored in the sensitivity analysis of potential rebound effects.

	Income effects			Re-spending				
Rebound scenario	Data	SEK	Source	Type of marginal consumption	Share of users re-spending on marginal consumption (%)	Source	Carbon intensity of marginal consumption (g CO_2-eq./SEK)	Source
RE1, 2U1 users	50% of secondhand resale price (as explained in Section 2.1)	965	User survey	Shell jacket consumption	38%	User survey	6	Calculations based on user survey
RE2, 2U1 users	50% of secondhand resale price (as explained in Section 2.1)	965	User survey	Average marginal consumption in Sweden	38%	User survey	47	Konsumentverket (2018)
RE3, 2U2 users	Average original sales price—average secondhand sales price	1871	User survey	Tourism, global	10%	User survey	100	Lenzen et al. (2018)

income effects are probably limited for many users in this case, three potential re-spending type rebound effects (RE) are investigated for the shares of users who can be assumed to experience income effects based on the surveys[4] (André & Björklund, 2023) (Table 4): 2U1 users re-spending on shell jackets (RE1) or alternatively average Swedish marginal consumption (RE2) and 2U2 users re-spending on travel (RE3). RE1 and RE3 are simplified scenarios based on the reported marginal consumption whereas RE2 is hypothetical, based on the idea that users themselves may not know what their marginal consumption might be. RE1 assesses the potential rebound effect discussed by André and Björklund (2023) that the existence of secondhand stores could intensify the consumption of the group of 2U1 users referred to as "regulars."[5] The assessment of rebound effects is limited to the sensitivity analysis and FU1 for the sake of clarity and conciseness, and to climate change impacts due to data availability.

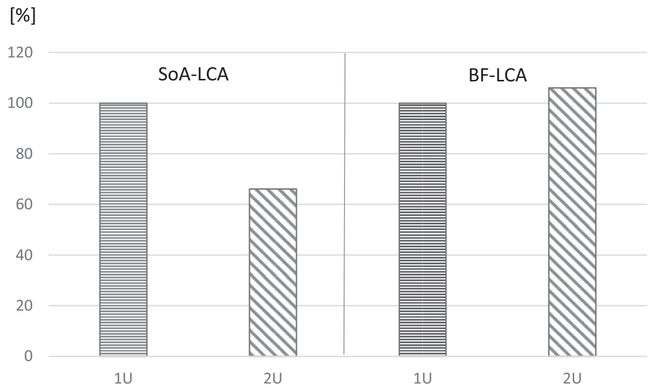

FIGURE 2 Comparisons of 1U (one-user) and 2U (two-user) life cycles according to SoA (state-of-the-art) and BF (baseline framework) life cycle assessments (LCAs) in terms of climate change impacts. The impacts of each 2U life cycle are normalized to its respective 1U life cycle. The underlying data for this figure can be found in Supporting Information S2. CE, circular economy.

4 | ENVIRONMENTAL PERFORMANCE OF REUSE OF SHELL JACKETS

This section is divided into two parts: a comparison between the SoA and BF LCAs (Section 4.1) and sensitivity analyses (Section 4.2). In the main article, the focus is on climate change impacts. Most other impact categories have similar result patterns and are presented in Supporting Information S1.

4.1 | Comparison of SoA-LCA versus BF-LCA

The purpose of this section is to exemplify how using the framework to conduct CE LCAs may influence results and interpretations of the environmental performance of CE measures. Accordingly, Figure 2 compares the results of the SoA and the BF LCAs. In the SoA-LCA, the 2U life cycle has about 34% less impact compared to the 1U life cycle. In the BF-LCA, however, the 2U life cycle instead has about 6% higher impact than the 1U life cycle. The main reason for the contradictory results is the modeling of how much relative use extension is enabled by the secondhand stores. In the SoA-LCA, secondhand sales are assumed to extend the use of shell jackets from 4 (1U) to 6.5 (2U) years, in other words, a 62.5% use extension. In the BF-LCA, however, the lifespan of the 2U-life cycle is only slightly longer than that of the 1U life cycle (9.7 compared to 7.9, see Figure 1), resulting in a use extension of merely 23%. Another key reason is the displacement rate, which is assumed to be perfect (100%) in the SoA but only 75% in the BF (the influence of displacement rates is further demonstrated in Section 4.2.3).

4.2 | Sensitivity analyses of F-LCA

The purpose of the sensitivity analysis is to demonstrate how methodological choices and modeling approaches concerning functional unit definition, reference scenarios, displacement rates, and rebound effects may influence results of CE LCAs.

4.2.1 | Functional unit definition

Figure 3 illustrates the influence of the functional unit definition on the comparison between 1U and 2U life cycles of the F-LCA: based on 1 year (FU1) or 100 use occasions (FU2) and assuming constant (a) or deteriorating functionality (b). As demonstrated in Section 4.1 (where FU1 is used), the 2U life cycle has higher impacts than the 1U life cycle because of imperfect displacement and the finding that the lifespans of both alternatives are, in fact, quite similar (7.9 vs. 9.7 years, respectively). With FU2, the 1U life cycle causes about 40% less environmental impact than the 2U life cycle (Figure 3). This substantial difference is mainly due to the higher frequency of use among 1U users compared to 2U users and the resulting number of use occasions (800 vs. 625 (André & Björklund, 2023) and summarized in Section 2). Additional reasons for this difference are imperfect displacement and reuse efficiency, in other words, that only 90% of shell jackets handed in for resale are reused (Supporting Information S1).

Accounting for functionality deterioration over time only affects the results slightly: The difference between the 1U and 2U life cycles with these functional unit definitions (FU1b and FU2b) are within 2% compared to the results with their constant functionality counterparts (FU1a and FU2a)

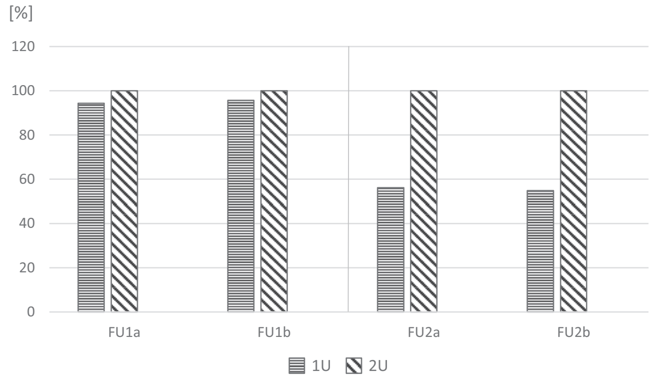

FIGURE 3 Sensitivity analysis of the influence of functional unit definitions, FU1a,b and FU2a,b, on the comparison between one-user (1U) and two-user (2U) life cycles of the F-LCA, in terms of climate change impacts. The underlying data for this figure can be found in Supporting Information S2. LCA, life cycle assessment.

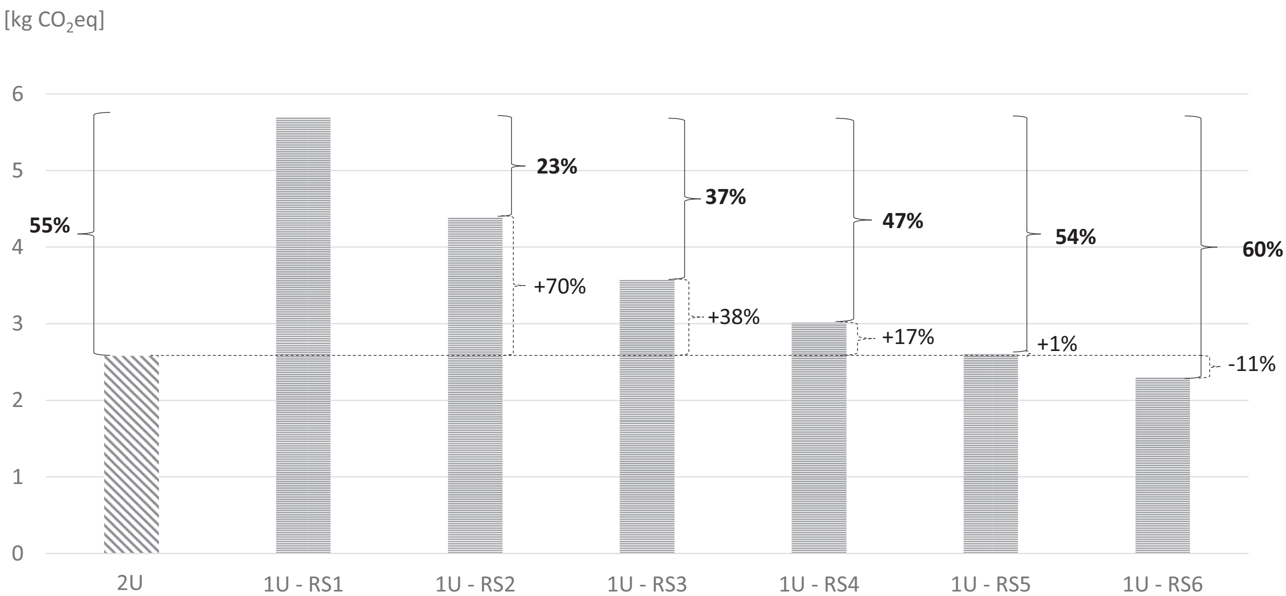

FIGURE 4 Sensitivity of reference scenario with FU1—1 year of shell jacket use: the two-user (2U) life cycle (left) compared to hypothetical reference scenarios (RS) where 2U users do not resell and instead: RS1: discard them after U1 (= 3.4 years) or RS2–RS6: use them for an additional 1—5 years. Percentages represent relative changes in climate change impact compared to the worst-case, RS1 (black brackets), and to the 2U life cycle (dashed brackets). The underlying data for this figure can be found in Supporting Information S2.

(Figure 3). With FU1, impacts of 1U and 2U life cycles are slightly more similar when accounting for functionality deterioration (FU1b) compared to when assuming constant functionality (FU1a). With FU2, on the other hand, the results are slightly more dissimilar when accounting for functionality deterioration (FU1b) compared to when assuming constant functionality. This is because shell jackets in the 1U life cycle are used more often at the beginning of the life cycle when functionality is highest. In the 2U life cycle, shell jackets are fairly idle at the beginning of the life cycle, when their functionality is highest, thus not delivering as much function. The overall similarity between results with constant and deteriorating functionality is because the life cycles, 1U and 2U, are similar in terms of both lifespan and functionality deterioration over time. Thus, it could be more important to account for functionality deterioration in cases where compared alternatives are not as similar as they are in this case, for example, if products in a 1U life cycle would be discarded prematurely at higher levels of functionality than in a 2U life cycle.

4.2.2 | Reference scenario

Figure 4 demonstrates how the 2U life cycle compares to hypothetical reference scenarios (1U life cycles) in which secondhand stores did not exist and the shell jackets of 2U1 users would instead: (1) be discarded and (2–6) be used for an additional 1–5 years by the same user. Unsurprisingly, the

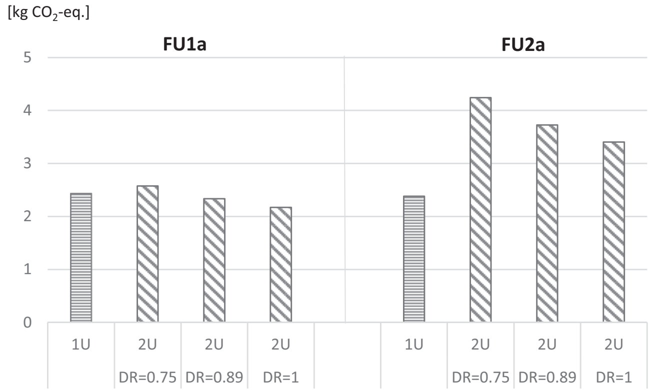

FIGURE 5 Climate change impacts for the one-user (1U) and two-user (2U) life cycles per functional unit with three displacement rates: $DR_M = 0.75$; $DR_M = 089$; $DR_P = 1$. The underlying data for this figure can be found in Supporting Information S2. DR_M, market-based displacement rate; DR_P, perfect displacement rate.

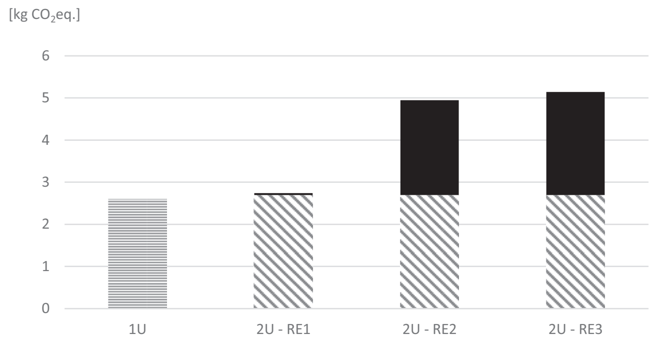

FIGURE 6 Influence of potential rebound effects (in black) on climate change impacts per FU1a. Horizontal stripes = life cycle impacts of one-user (1U) life cycle; diagonal stripes = life cycle impacts of two-user (2U) life cycle; black = rebound effect impacts. Scenarios of re-spending on marginal consumption: RE1: 38% of 2U1 users spend potential income effect from secondhand resale on shell jacket consumption; RE2: 38% of 2U1 users spend potential income effect from secondhand resale on Swedish average marginal consumption; RE3: 10% of 2U2 users spend potential income effect from the secondhand discount on tourism. The underlying data for this figure can be found in Supporting Information S2. DR, displacement rate.

2U life cycle is preferable compared to 1U life cycles with relatively short lifespans, such as RS1–RS3 (Figure 4). Compared to the worst-case (RS1), the 2U life cycle causes 55% less climate change impact. Naturally, for each additional year added to the lifespan of the 1U life cycle, the impacts decrease per year of shell jacket use. There is a break-even point (i.e., impacts of the alternatives are equal) when the 1U life cycle has a lifespan of around 7.4 years.

4.2.3 | Displacement rates

Figure 5 demonstrates the influence of displacement rates on the environmental performance of reuse. With FU1, the choice of displacement rate influences whether the 2U life cycle is favorable to the 1U life cycle or not: DR_M has around 6% higher impact, while DR_T and DR_P have around 4% and 11% lower impact than the 1U life cycle, respectively. With FU2, the 2U life cycle has a substantially higher impact regardless of displacement rate, due to the higher frequency of use among 1U users compared to 2U users. In this case, the displacement rate influences how much worse the 2U life cycle performs in terms of climate change impact compared to the 1U life cycle (about 78%, 57%, and 43%, respectively).

4.2.4 | Rebound effects

RE1, which represents 2U1 users re-spending on shell jackets, has negligible climate change impacts (Figure 6) since the carbon intensity of shell jacket consumption is low (Table 4). Income effects spent on other types of consumption (average marginal consumption in Sweden and tourism, respectively), however, cause substantial climate change impacts. In these scenarios (RE2 and RE3), rebound effects may increase climate change impacts of the 2U life cycle substantially (84% and 91%, respectively) so that total climate impacts are about double compared to the 1U life cycle.

5 | DISCUSSION

This paper demonstrates how the comprehensive mapping guided by the proposed framework can inform the LCI and the goal and scope of CE LCAs and how this may influence results and conclusions about the environmental performance of CE measures. A key result of the comprehensive mapping was that lifespans of both 1U and 2U shell jackets are in this case fairly similar, implying a less substantial use extension compared to what would typically be assumed in SoA CE LCAs. As a result, potential environmental benefits of reuse are, at best, very limited when using functional units defined on the basis of time during which shell jackets are active parts of users' wardrobes (FU1a,b). Another key result of the comprehensive mapping was the comparatively low frequency of use during the first use span of secondhand shell jackets (André & Björklund, 2023). This implies that 1U life cycles result in considerably less environmental impact than 2U life cycles with functional units defined on the basis of use occasions (FU2a,b).

On the whole, these environmental results based on the comprehensive framework mapping call for a more cautious stance about the environmental promise of secondhand sales. However, as discussed by André and Björklund (2023), it needs to be kept in mind that the quantitative data of the mapping are based on a limited sample of user survey respondents (1U: $n = 20$; 2U1: $n = 30$; 2U2: $n = 21$). In addition, the use of surveys implies that the accuracy of the data could be influenced by the intention–behavior gap, in other words, the discrepancy between what people say and do (Sheeran & Webb, 2016). On the other hand, the stated behaviors of the survey data were well-aligned with the observations on behavior reported by store managers (André & Björklund, 2023). Furthermore, in line with the reasoning of Daae and Boks (2015), the comprehensive mapping can be seen as a foundation for making more well-informed assumptions about the use phase than without the framework, rather than a foundation for an accurate model of reality. Therefore, the important contribution of this paper is not the exact environmental results of the case study, but the demonstration of how mapping the use phase more comprehensively than SoA can influence CE LCA results and deepen our understanding of environmental performance of CE measures. For example, the short use span and low frequency of use of 2U1 users would not have been identified and modeled in SoA CE LCAs. Although not statistically significant nor generalizable by default to other cases, the importance of such data is demonstrated through the comparison between the SoA and BF LCAs of the case study and the results with a functional unit based on use occasions (FU2).

A prominent outdoor brand expects the lifespan of one of their high-quality shell jackets to be limited to 1000 use occasions (Böckin, Goffetti et al., 2020; Goffetti et al., 2022). This implies that the 1U life cycle (825 use occasions) approaches the maximum expected technical lifespan of high-quality shell jackets and thus represents a fairly ideal life cycle in this regard. With this in mind, it should not be surprising that the 2U life cycle in many scenarios has a higher environmental impact than the fairly ideal 1U life cycle. Compared to other, less ideal, reference scenarios, the 2U life cycle is in most cases favorable. Thus, the overall takeaway from collecting real data on product use and user behavior is that 2U life cycles represent a "second best" alternative to 1U life cycles, which are fairly ideal. This reinforces the important conclusion that circular life cycles are not intrinsically environmentally preferable to linear ones (Zink & Geyer, 2017). What matters are important variables such as lifespan, frequency of use, and displacement rates which yield different levels of delivered function during product–user life cycles. Nonetheless, the conclusion from these comparisons should not be that 2U life cycles are to be discouraged. Instead, given that some users will want to sell shell jackets before their technical lifespans are reached, 2U life cycles are bound to happen. In such cases, reuse through secondhand stores entails a reduction of environmental impacts compared to a reference scenario where such shell jackets would not be used further (RS1). In other words, the results do not imply that 2U2 users should stop purchasing secondhand shell jackets and buy new ones instead. This could imply that a higher share of secondhand shell jackets would not be sold, shifting the system toward approaching the worst-case scenario (RS1). On the other hand, if there is less demand for secondhand shell jackets, it could imply that 2U1 users would use the ones they have for longer, corresponding to the other scenarios (RS2–RS6), of which some are environmentally preferable to the 2U life cycle.

Further, accounting for imperfect displacement can alter conclusions about whether 2U life cycles result in lower environmental impact than 1U life cycles. With FU1a-b, the 2U life cycle has a lower environmental impact if displacement rates are based on a market equivalency approach but higher if based on a technical equivalency approach or if assuming perfect displacement. Thus, as cautioned by, for instance, Zink and Geyer (2017), not collecting real data on displacement risks overestimating the potential benefits of reuse and failing to identify cases where 2U life cycles have higher environmental impacts than 1U life cycles.

Siderius and Poldner (2021) argue for the importance of distinguishing between "relevant and less relevant instances of a rebound in light of the transition" toward CE. Here, a clear distinction can be made between RE1 and the other two rebound scenarios (RE2 and RE3). RE1, which has been argued to represent the potential of "regulars" to intensify their consumption due to the existence of secondhand stores, has negligible impacts whereas the other scenarios almost double the impacts of the 2U life cycle. This implies that consumption of shell jackets (and other products with low carbon intensity per price) could, paradoxically, be encouraged since they bind financial resources which otherwise could be spent on more impactful consumption. RE2 and RE3 can be compared to the assessment by Makov and Font Vivanco (2018) of the rebound effects of secondhand sales of mobile phones. They find that rebound effects can offset the environmental benefits of reuse, resulting in 1U and 2U life cycles with comparable total impacts. In this case, rebound effects rather add significant impacts to the 2U life cycle whose benefits compared to the 1U life cycle are, at best, small to begin with.

6 | CONCLUSIONS

This paper has tested the use of a framework intended to facilitate accounting for commonly oversimplified aspects in CE LCAs related to the use phase of consumer products. For this purpose, a case study was deployed focusing on the reuse of shell jackets enabled by premium secondhand outdoor stores. A previous paper presented a comprehensive mapping of the case study guided by the framework (André & Björklund, 2023), while this paper used the mapping as input to a CE LCA to demonstrate how the framework can be used to contribute to a deeper and more nuanced understanding of the environmental performance of CE measures.

Addressing the data gap on real user behavior data (Harris et al., 2021; Polizzi di Sorrentino et al., 2016; Suski et al., 2021), the comprehensive mapping (André & Björklund, 2023) revealed that shell jackets have similar lifespans regardless of whether they include one or two use spans (referred to as 1U and 2U life cycles) and that shell jackets in 1U life cycles are used for a higher number of total use occasions (André & Björklund, 2023). Using such findings as input to CE LCA, this paper demonstrates that conclusions about the environmental performance of reuse can easily be altered whether studied product–user life cycles are based on real user behavior data or not, and whether imperfect displacement and rebound effects are considered. In addition, especially if defining the functional unit based on use occasions (FU2), life cycles that are commonly labeled "circular" may have a significantly higher environmental impact than "linear" ones, because "circular" products may be used less frequently, in particular during their first use span. On the whole, these environmental results call for a more cautious stance with regard to the environmental promise of reuse through secondhand sales and other CE measures.

Altogether, by uncovering new insights into the environmental performance of reuse and its underlying mechanisms, the framework seems capable of supporting a better understanding of the environmental performance of CE measures. However, the current version is intended to be comprehensive, but not exhaustive, in terms of aspects that may shape product–user life cycles and ultimately environmental performance of CE measures. Application in other sectors and to other CE measures than reuse is likely to develop the framework further and simultaneously improve understanding of the environmental performance of such measures. Another research avenue is to test the usefulness of the framework more broadly, for instance, as a tool for life cycle thinking and design.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supporting information of this article and the article by André and Björklund (2023) and its supporting information.

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NOTES

[1] For a more thorough understanding of these results, the reader is referred to André and Björklund (2023).

[2] The functionality deterioration is based on the perceived functionality as assessed by users. The data on measured functionality could also be used for this purpose. Since the measured functionality declines more slowly than perceived functionality (André and Swenne, 2023), this would result in a smaller difference compared to the version with constant functionality.

[3] The mapping revealed that another key feature of reuse, at least in this case, is that reuse increases the frequency of use from rather low (33 use occasions per year) to a frequency of use more comparable (80) to that of the 1U life cycle (102 use occasions per year) (André and Björklund, 2022).

[4] Users who claimed to have spent money, reimbursed, or saved from engaging with secondhand stores, on a specific marginal consumption, such as shell jackets or travel, were assumed to have experienced income effects. Marginal consumption, in turn, refers to the set of goods and services consumed (on the margin) as a result of an income effect.

[5] Rather than assessing the potential shortening of 2U1 users' use spans compared to a counterfactual scenario where the secondhand stores did not exist (André and Björklund, 2023), RE1 accounts for their additional consumption occurring within the same use span. In other words, during the use span of 3.4 years, the "regulars" not only consume the first shell jacket but also a portion of an additional one, corresponding to the financial reimbursement from the resale of the first one.

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SUPPORTING INFORMATION

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