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Tracking important Environmental Impacts Related to Domestic Consumption

A Feasibility Study on Environmental Life Cycle Indicators for Land Use/Biodiversity, Air Pollution, Nitrogen, Water Use, and the Use of Materials

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Abbreviations and Glossary

AoP	Area of Protection
BAFU	Bundesamt für Umwelt, see FOEN
BDP	Biodiversity Damage Potential
BDM	Biodiversity Monitoring Switzerland
BFS	Bundesamt für Statistik, see SFO
CF	Characterisation Factor
DALY	Disability-adjusted life years
DK	Denmark
DMC	Domestic Material Consumption
DMI	Domestic Material Input
EC	European Commission
EMC	Environmentally Weighted Material Consumption
EP	Eco-point
EWR	Environmental water requirement
FAO	Food and Agriculture Organization
FOEN	Federal Office for the Environment
GIS	Geographic information system
HANPP	Human Appropriation Net Primary Production
LCA	Life cycle assessment
LCI	Life cycle inventory analysis
LCIA	Life cycle impact assessment
MRIO	Multi-Regional Input-Output
NEEDS	New Energy Externalities Development for Sustainability (www.needs-project.org)
NPP	Net Primary Production
OECD	Organization for Economic Cooperation and Development
PAF	Potentially affected fraction of species
PDF	Potentially disappeared fraction of species
PSD	Particulate size distribution
REI	Correlation Coefficient Environmental Impact
REQ	Correlation Coefficient Ecosystem Quality
RHH	Correlation Coefficient Human Health
RMC	Raw Material Consumption
RME	Raw Material Equivalent
RR	Correlation Coefficient Resources
SFO	Swiss Federal Office of Statistics
SOM	Soil Organic Matter Content
TMC	Total Material Consumption
TMR	Total Material Requirement
UNEP	United Nations Environment Programme
WSI	Water stress index

Executive Summary

Motivation and goal of the study

In a globalised world, consumption in one country may cause significant environmental impacts abroad. This is especially true for small open economies with high shares of imported goods, such as Switzerland. For this reason information on important impacts of domestic consumption on the planetary environment are important for environmental policy decisions.

For some specific environmental aspects, so far primarily for climate change, time series including the impact abroad have already been published. But climate change is only one of the critical planetary boundaries. It is thus important to track impacts of domestic consumption on other critical planetary boundaries, such as those related to water use, land use/biodiversity, eutrophication/nitrogen, or air pollutants. Another challenge is the appropriate tracking of environmentally relevant materials as a key driver of environmental impacts. In this feasibility study, indicators representing these issues are analysed and evaluated.

Approach and key issues addressed

The mandate for this study required that the analysed indicators are based on physical, chemical or biological relationships. Aggregation schemes substantially influenced by political or subjective value judgements were not within the scope of this study.

The recommendation for indicators for each environmental aspect is based on the quality requirements applied by the Swiss Federal Office for the Environment (FOEN) for environmental information. Thus, the key requirements analysed for a "True and Fair View" are environmental relevance and focus on the overall picture. Furthermore, the compliance to these key requirements preconditions a good performance regarding reliability, transparency, comprehensibility, coherence and comparability, availability of information, and timeliness (up-to date information). Finally, ease of implementation has been added as a further criterion, which as well is very important for its future use. The rating of the environmental relevance and focus on the overall picture are based on a quantitative comparison of the different indicators using correlation analyses of the characterisation factors, the environmental indicator results and a damage assessment, where applicable or available.

Results

The study recommends the following indicators:

- Biodiversity damage potential according to de Baan for land use,
- Particulate matter formation according to ReCiPe for air pollution,
- Marine eutrophication according to ReCiPe for Nitrogen and eutrophication,
- Water stress index according to Pfister for water use,
- The environmentally weighted material consumption (EMC) for the use of environmentally relevant materials, total material consumption (TMC) in case weighted indicators are not acceptable.

Biodiversity is considered the most important environmental impact of land use. The **land use indicator** according to de Baan & Olson quantifies the damage potential of land use on biodiversity. The indicator quantifies biodiversity losses related to a broad selection of different plants and animals. The impact on biodiversity of a specific type of land use in different biomes of the world is extrapolated using species richness data of these biomes.

The **particulate matter (primary and secondary) indicator** according to ReCiPe is a measure of the quantity of primary and secondary particulates emitted and formed, respectively. The indicator is representative for human health damages caused by air pollution due to the consumption of goods and services.

The **marine eutrophication indicator** according to ReCiPe quantifies the amount of nitrogen ending up in Oceans due to the release of nitrogen compounds to air, water and the soil.

The **water use indicator** according to Pfister (water stress index, WSI) quantifies the water stress in a specific region. It shows the highest correlation with damages on resources, human health and ecosystems of all indicators examined. Regional and even local water stress indicators require regionalised life cycle inventory data. This is the main challenge with regard to ease of implementation.

The **environmentally weighted material consumption** (EMC) is an indicator which is able to point out in a sufficiently precise manner the most environmentally relevant material consumption. All other indicators analysed overestimate the relevance of materials with a high mass but with low specific environmental impacts such as mineral resources.

An aggregation across different environmental impacts always needs some form of judgement. For indicator sets that exclude the use of explicit weights we recommend the **total material consumption (TMC)** because this indicator comes closest to environmental impact related indicators.

Greenhouse gas emissions:

The quantification of the climate change impact of Swiss consumption has a long tradition. In 2000 the grey greenhouse gas emissions of the energy and the food and beverage sectors in the years 1990 and 1998 were quantified for the first time. In 2007, the scope was extended to cover the grey greenhouse gas emissions of Swiss consumption between 1990 and 2004. In 2011 the scope was further extended in a pilot study to quantify the environmental impacts of Swiss consumption and production in 2005. Currently, the knowledge gained in the pilot study is being used to establish a time series covering 1996 to 2011 of the environmental impacts (including greenhouse gas emissions) of Swiss production and consumption. In all these studies, greenhouse gas emissions were assessed using the most recent global warming potential factors published by the Intergovernmental Panel on Climate Change (IPCC) and including all substances contributing to climate change (i.e. including chlorofluorocarbons, hydrochlorofluorocarbons and halons).

The study states that the analysed environmental issues can already be discribed with existing methods in a quality allowing their use in official environmental reports. In order to include the impacts abroad, the indicators are the result of a model, rather than of a mere measure. This allows them to show the reliable overall picture on the environmental issue, but, logically, their direct physical verification is not possible. While ready to use, some methodological issues are still being refined, such as the further development of methodologies and of LCA databases, while other challenges may probably remain unresolved, such as the complete traceability of goods and transparence on the latter's composition.

The overall evaluation shows that there are no perfect indicators available yet. However, the drawbacks are of minor importance compared to the environmental relevance of the topic they address.

Recommendations

The five indicators recommended cover the topics water use, land use, use of environmentally relevant materials, air pollution and nitrogen fixation / eutrophication. The indicator "environmentally weighted material consumption" (EMC), representing "environmentally relevant materials", should be used independently of the other four indicators, because it is a cross cutting indicator.

The indicators representing land use, water use, air pollution and eutrophication and the climate change indicator address different important environmental impacts and damages to human health, ecosystems and resources. Although they are not part of one common environmental impact assessment method scheme, they (except EMC) are suited to be used together.

The following environmental impacts of global or national concern or environmental issues are not or only marginally covered by the indicators discussed in this report:

acidification, ecotoxicity, cancer and non-cancer toxicity, ionising radiation (i.e. radiation which is generated through nuclear reactions), noise, depletion of biotic resources, depletion of mineral primary and energy resources and radioactive waste.

Ecotoxicity, noise, and nuclear waste are considered the most important environmental impacts not yet covered by the indicators discussed in this report (apart from climate change). Reduced availability, lower quality and large variability in data are main challenges with regard to toxicity related environmental impacts and to impacts on human health caused by noise. It is recommended to evaluate them in a next phase.

The relative changes in environmental impacts of Swiss consumption in the course of time quantified with the indicators recommended in this study are more reliable than their absolute amounts. However, the absolute amounts are of interest and importance as soon as target values are being defined.

The proposed indicators helps to reveal whether environmental progress is due to real improvements or whether environmental impacts are rather shifted abroad. The indicators help to better understand the progress of a country respecting its planetary boundaries.

Zusammenfassung

Hintergrund und Ziel der Studie

In einer globalisierten Welt kann der inländische Konsum von Gütern erhebliche Belastungen im Ausland verursachen, besonders bei kleinen Volkswirtschaften wie der Schweiz mit einem grossen Handelsvolumen an importierten Gütern. Um informierte umweltpolitische Entscheidungen zu treffen, ist es deshalb wichtig, die globalen Umweltauswirkungen des inländischen Konsums zu kennen.

Bisher wird eine Zeitreihe insbesondere der Treibhausgas-Emissionen des Schweizer Konsums, inklusive der ausländischen Emissionen erfasst und publiziert. Der Klimawandel ist jedoch nur eine von vielen kritischen planetaren Grenzen. Es ist deshalb wichtig, die Umweltauswirkungen des Schweizer Konsums auch für weitere, global wichtige Umweltthemen zu quantifizieren, wie Wasser- oder Landnutzung/Biodiversität, Überdüngung/Stickstofffixierung und Luftverschmutzung. Eine weitere Herausforderung ist die angemessene Bewertung des Konsums umweltrelevanter Materialien. In der vorliegenden Machbarkeitsstudie werden Indikatoren zu den genannten Themenbereichen analysiert und ausgewertet.

Ansatz und Schlüsselkriterien

Gemäss Vorgabe dieser Studie basieren alle analysierten Indikatoren auf physikalischen, chemischen oder biologischen Zusammenhängen. Deshalb werden Aggregationsmethoden, welche politische oder subjektive Gewichtungen beinhalten, in dieser Studie nicht näher analysiert.

Der Vergleich der verschiedenen Indikatoren basiert auf den „True and Fair“ Qualitätsanforderungen an Umweltinformationen, welche vom Bundesamt für Umwelt (BAFU) angewendet werden. Die Schlüsselkriterien der Qualitätsanforderungen an Umweltinformationen sind Umweltrelevanz und Fokus auf das Gesamtbild. Zusätzlich werden die Kriterien Verlässlichkeit, Transparenz, Verständlichkeit, Kohärenz und Vergleichbarkeit, Verfügbarkeit von Informationen und Aktualität analysiert. Das Kriterium Einfachheit der Implementierung wurde neu zum Satz der Bewertungskriterien hinzugefügt, weil dieses Kriterium entscheidend ist für die zukünftige Nutzung der jeweiligen Indikatoren. Die Bewertung der Umweltrelevanz und des Fokus auf das Gesamtbild basieren auf einem quantitativen Vergleich der verschiedenen Indikatoren mittels einer Korrelationsanalyse der Charakterisierungsfaktoren und der bewerteten Umweltauswirkung, falls diese vorhanden und anwendbar sind.

Resultate

Es werden folgende Indikatoren empfohlen:

- Biodiversitäts-Schadenspotenzial nach de Baan für die Landnutzung
- Feinstaub (primär und sekundär) nach ReCiPe für die Luftverschmutzung
- Marine Eutrophierung nach ReCiPe für Überdüngung/Stickstofffixierung und
- Wasserstressindex nach Pfister für die Wassernutzung
- Umweltgewichteter Materialverbrauch (EMC) für die Nutzung von umweltrelevanten Materialien, sowie dem totalen Materialkonsum (TMC) in Fällen, in denen gewichtete Indikatoren nicht erwünscht sind

Auswirkungen auf die **Biodiversität** werden als die wichtigsten Umweltauswirkungen der Landnutzung angesehen. Der Indikator nach de Baan & Olson zur Bewertung der Landnutzung quantifiziert das Schadenspotenzial der Landnutzung bezogen auf die Biodiversität. Der Indikator quantifiziert den Rückgang der Biodiversität basierend auf einer breiten Auswahl von verschiedenen Pflanzen- und Tierarten. Die Auswirkung von spezifischen Landnutzungsarten auf die Biodiversität wird für verschiedene Biome auf der ganzen Welt extrapoliert basierend auf der Artenvielfalt der einzelnen Biome.

Der Indikator **Feinstaub (primär und sekundär)** nach ReCiPe hat als Grundlage die Menge der emittierten und gebildeten Primär- und Sekundärpartikel und bildet gestützt darauf die Auswirkungen der Luftschadstoffe auf die menschliche Gesundheit ab.

Der Indikator **marine Eutrophierung** nach ReCiPe quantifiziert die Menge an Stickstoff, welche potenziell durch die Emission von Stickstoffverbindungen in Wasser, Luft und Boden in die Ozeane gelangt.

Der **Wasserstressindex** nach Pfister (WSI) quantifiziert die Wasserknappheit in einer spezifischen Region. Er zeigt die beste Korrelation mit Auswirkungen auf Ressourcen, auf die menschliche Gesundheit und auf die Ökosysteme. Regionale und lokale Wasserstressindikatoren benötigen regionalisierte Sachbilanzdaten. Die Verfügbarkeit von regionalisierten Daten ist die grösste Herausforderung im Hinblick auf die Implementierung dieses Indikators.

Der **umweltgewichtete Materialverbrauch (EMC)** ist der Lage, die umweltrelevantesten Materialverbräuche einigermassen zuverlässig zu erfassen. Alle anderen analysierten Indikatoren überschätzen die Bedeutung von mineralischen Ressourcen mit einem hohen Gewicht aber geringen Umweltauswirkungen wie Sand oder Kies.

Die Aggregation über mehrere Kategorien von Umweltauswirkungen hinweg setzt immer Werturteile voraus. Für Indikatorensets, welche die Nutzung von expliziten Gewichtungen ausschliessen, empfehlen wir den **totalen Materialkonsum (TMC)**. Dieser Indikator steht den umweltauswirkungsorientierten Indikatoren am nächsten.

Treibhausgas-Emissionen:

Die Quantifizierung der durch den Schweizer Konsum verursachten Treibhausgas-Emissionen hat in der Schweiz eine lange Tradition. Im Jahr 2000 wurden erstmals die Grauen Treibhausgas-Emissionen des Energie- und Ernährungssektors für die Jahre 1990 und 1998 quantifiziert. Im Jahr 2007 wurde der Untersuchungsrahmen auf die Grauen Treibhausgas-Emissionen des gesamten Schweizer Konsums auf die Jahre 1990 bis 2004 erweitert. Im Jahr 2011 wurden in einer Pilotstudie die gesamten Umweltauswirkungen des Schweizer Konsums und der Schweizer Produktion für das Jahr 2005 quantifiziert. Zur Zeit werden die aus der Pilotstudie gewonnenen Erfahrungen genutzt, um eine Zeitreihe des Umweltauswirkungen des Schweizer Konsums und der Schweizer Produktion (inklusive Treibhausgas-Emissionen) für die Jahre 1996 bis 2011 zu erstellen. In allen diesen Studien wurden die aktuellsten Treibhauspotenzial-Faktoren gemäss Intergovernmental Panel on Climate Change (IPCC) verwendet und alle Substanzen berücksichtigt, welche einen Beitrag zum Klimawandel leisten (inklusive Fluorchlorkohlenwasserstoffe (FCKW), teilhalogenierter Fluorchlorkohlenwasserstoffe (H-FCKW) und Halone).

Gemäss den Ergebnissen dieser Studie können die mit den heute vorhandenen Daten und Methoden analysierten Umweltaspekte in der Konsumperspektive in einer Qualität gemessen und dargestellt werden, die deren Verwendung in der offiziellen Berichterstattung erlaubt. Weil dabei auch die im Ausland anfallenden Emissionen und Verbräuche mit einbezogen werden, ist der Indikator zwangläufig das Resultat einer modellbasierten Berechnung und nicht einer physikalischen Messung. Die Indikatoren geben somit zum jeweils betroffenen Umweltaspekt ein zuverlässiges Bild über die gesamten durch den Konsum verursachten *potenziellen* Umweltauswirkungen. Sie können aber nicht direkt verifiziert oder falsifiziert werden. Die methodischen Ansätze und die Daten stehen bereits heute zur Verfügung, auch wenn sie im Zuge der stetigen Entwicklungen in der Ökobilanzierung laufend verbessert werden (z.B. wachsendes Angebot an immer vollständigeren Ökobilanz-Datenbanken oder Verfeinerung der Analysemethoden). Gewisse Herausforderungen können voraussichtlich nicht behoben werden und werden somit weiterhin Vereinfachungen und Annahmen voraussetzen (v.a. bezüglich der Transparenz in der Herkunft und Zusammensetzung der Import- und Exportgüter und deren Flüsse im Inland).

Die Gesamtbeurteilung zeigt, dass die heute verfügbaren Indikatoren nicht perfekt sind. Die Mängel sind aber gegenüber der Relevanz der von ihnen adressierten Umweltthemen von untergeordneter Bedeutung.

Empfehlungen zum weiteren Vorgehen

Die fünf empfohlenen Indikatoren decken die Umweltbereiche Wassernutzung, Landnutzung, umweltrelevante Materialien, Luftverschmutzung und Stickstofffixierung/Eutrophierung ab. Der Indikator umweltgewichteter Materialverbrauch (EMC) zur Erfassung des Konsums von umweltrelevanten Materialien soll unabhängig von den anderen Indikatoren verwendet werden, da es ansonsten zu Doppelzählungen von Umweltauswirkungen kommt.

Die Indikatoren zur Bewertung von Landnutzung, Wassernutzung, Luftverschmutzung und Eutrophierung sowie der Indikator für Klimawandel adressieren wichtige Auswirkungen auf die menschliche Gesundheit, auf Ökosysteme und auf Ressourcen. Obwohl sie nicht Teil einer bestimmten Bewertungsmethode sind, können diese Indikatoren mit Ausnahme des EMC zusammen angewendet werden.

Die folgenden Umweltauswirkungen oder Umweltbereiche von globaler und nationaler Bedeutung sind in dieser Studie nicht oder nur am Rande analysiert und diskutiert worden: Versauerung, Ökotoxizität, Humantoxizität, ionisierende Strahlung, Lärm, Nutzung von biotischen, mineralischen und Energieressourcen und radioaktive Abfälle. Ökotoxizität, Lärm und nukleare Abfälle werden (abgesehen vom Klimawandel) als die wichtigsten Umweltbereiche angesehen, welche in diesem Bericht nicht thematisiert werden. Die limitierte Verfügbarkeit, die noch bescheidene Qualität und die grosse Variabilität der Daten sind die grössten Herausforderungen in Bezug auf toxizitäts- und lärmbedingte Auswirkungen auf die menschliche Gesundheit. Wir empfehlen die Auswertung dieser Umweltbereich in einer weiterführenden Analyse.

Die empfohlenen Indikatoren erlauben es zu erkennen, ob eine Umweltverbesserung einem tatsächlichen Fortschritt entspricht, oder ob inländische Verbesserungen hauptsächlich auf Verlagerungen der Umweltbelastung ins Ausland zurückzuführen sind. Sie dienen somit dem besseren Verständnis des Fortschritts einer Volkswirtschaft, welche ihre planetare Grenzen respektiert.

Résumé

Contexte et objectif de l'étude

Dans un monde globalisé, la consommation de biens et de services d'un pays peut provoquer d'importants impacts environnementaux par-delà les frontières nationales. Cela est particulièrement vrai pour les petites économies ouvertes fortement dépendantes des importations comme la Suisse. Connaître l'influence de la consommation intérieure sur l'environnement mondial est donc essentiel pour l'élaboration de mesures de politique environnementale.

Pour certains aspects environnementaux tels que les changements climatiques, des séries chronologiques incluant les impacts transfrontaliers ont déjà été publiées. Les changements climatiques ne représentant que l'une des frontières planétaires, il importe de mesurer l'impact de la consommation intérieure sur les autres secteurs environnementaux (utilisation d'eau douce, utilisation des sols, recul de la biodiversité, eutrophisation/cycles de l'azote, pollution atmosphérique). L'évaluation de l'utilisation de matériaux ayant un impact sur l'environnement constitue un enjeu supplémentaire. La présente étude décrit et évalue un certain nombre d'indicateurs pour décrire et documenter ces problématiques.

Approche adoptée et problématiques abordées

Le mandat de l'étude imposait que les indicateurs définis soient de nature physique, chimique ou biologique. Des méthodes agrégatives influencées par des jugements de valeur politiques ou subjectifs n'ont donc pas été prises en compte.

Dans chaque domaine traité, les propositions d'indicateurs ont été formulées dans le respect des critères de qualité applicables aux informations environnementales de l'Office fédéral de l'environnement (OFEV). Ces critères reposent sur le principe de la représentation fidèle de la réalité (True and Fair View). Les principaux critères de qualité sont le caractère significatif de l'information et la priorité à la vue d'ensemble. Leur respect garantit la fiabilité, la transparence, la compréhensibilité, la cohérence, la comparatibilité, la disponibilité et l'actualité de l'information. A ces critères s'ajoute celui de la facilité de mise en œuvre, essentiel en vue de l'utilisation des indicateurs. Le caractère significatif de l'information et la priorité à la vue d'ensemble ont été évalués sur la base d'analyses de corrélation entre les critères de caractérisation, des résultats des indicateurs environnementaux et de l'évaluation des dommages, lorsque ces données étaient disponibles et utilisables.

Résultats

Nous recommandons l'utilisation des indicateurs suivants:

- potentiel d'atteinte à la biodiversité selon de Baan (aspect de l'utilisation des sols),
- les poussières fines selon ReCiPe (aspect de la pollution atmosphérique),
- eutrophisation marine selon ReCiPe (aspects des cycles de l'azote et de l'eutrophisation),
- indice de stress hydrique selon Pfister (aspect de l'utilisation d'eau douce),
- consommation environnementalement pondérée des ressources (aspect de l'impact environnemental de matériaux) ou consommation totale de ressources (si les indicateurs pondérés ne sont pas acceptables).

Le recul de la biodiversité est considéré comme le premier impact de l'utilisation des sols sur l'environnement. L'**indicateur de l'utilisation des sols** selon de Baan & Olson quantifie le potentiel de dommage sur la biodiversité, à savoir le recul de la biodiversité, évalué pour une vaste sélection d'espèces végétales et animales. L'impact sur la biodiversité d'un type particulier d'occupation du sol dans différents biomes est extrapolé grâce aux données disponibles sur l'abondance des espèces dans ces biomes.

L'**indicateur des poussières fines (particules primaires et secondaires** selon ReCiPe mesure la quantité de particules primaires et de particules secondaires émises. Il renseigne sur les effets sur la santé humaine de la pollution atmosphérique engendrée par la consommation de biens et de services.

L'**indicateur de l'eutrophisation marine** selon ReCiPe mesure les quantités de composés azotés rejetés dans les milieux naturels (air, eau, sol) qui parviennent dans les océans.

L'**indicateur de l'utilisation d'eau douce** selon Pfister (indice de stress hydrique, ISH) quantifie le stress hydrique dans une région donnée. Parmi tous les indicateurs, c'est celui qui présente la plus forte corrélation avec le recul des ressources et l'impact sur la santé humaine/les écosystèmes. Des indicateurs régionaux ou locaux de stress hydrique ne peuvent être définis que s'il existe des données régionales d'inventaire du cycle de vie. La mise en œuvre de l'indicateur dépend donc de la disponibilité de données régionalisées.

L'**indicateur de la consommation environnementalement pondérée des ressources** renseigne avec une précision suffisante sur l'utilisation de matériaux ayant un impact sur l'environnement. Tous les autres indicateurs analysés surestiment la nocivité des substances de poids élevé mais ayant un impact modéré sur l'environnement telles que les ressources minérales.

L'agréation de différents impacts sur l'environnement est normalement basée sur des estimations. Pour les systèmes d'indicateurs qui ne permettent pas de pondérations, nous recommandons d'utiliser la **consommation totale de ressources**, l'indicateur le plus proche des indicateurs d'impact sur l'environnement.

Emissions de gaz à effet de serre:

La quantification de l'impact de la consommation suisse sur les changements climatiques a une longue tradition. En 2000, une première étude a ainsi été consacrée aux rejets de gaz à effet de serre des secteurs de l'énergie et de l'industrie alimentaire entre 1990 et 1998. En 2007, la portée de l'étude a été étendue pour inclure les émissions de gaz à effet de serre de la consommation suisse entre 1990 et 2004. En 2011, une étude pilote s'est attachée à quantifier l'impact sur l'environnement de la consommation et de la production suisses en 2005. Les résultats de cette étude sont utilisés pour établir une série chronologique sur les impacts sur l'environnement de la production et de la consommation helvétiques pour les années 1996 à 2011 (émissions de gaz à effet de serre incluses). Dans l'ensemble de ces études, les rejets de gaz à effet de serre ont été évalués sur la base des derniers facteurs de potentiel de réchauffement publiés par le Groupe d'experts intergouvernemental sur l'évolution du climat (GIEC). Toutes les substances qui contribuent aux changements climatiques ont été prises en compte (y compris les chlorofluorocarbures, hydrochlorofluorocarbures et halons).

L'étude montre que les problématiques environnementales abordées peuvent être décrites au moyen de méthodes existantes dans une qualité qui autorise leur utilisation dans les rapports environnementaux officiels. Afin de pouvoir prendre en compte les impacts transfrontaliers, les indicateurs proposés sont le résultat de calculs modélisés plutôt que de mesures physiques. Ils fournissent une vue d'ensemble fiable, mais leur vérification directe est impossible. Certaines approches méthodologiques, bien que d'ores et déjà applicables, peuvent toujours être améliorées (méthodologies et bases de données ACV, p. ex.). Certains aspects tels que la traçabilité complète des produits et la transparence en matière de composition des produits resteront quant à eux probablement non résolus.

L'évaluation globale fait apparaître que les indicateurs disponibles ne sont pas parfaits. Leurs défauts sont toutefois négligeables comparés à la pertinence des thématiques environnementales couvertes.

Recommandations

Les cinq indicateurs proposés couvrent les domaines de la consommation d'eau douce, de l'occupation du sol, de l'utilisation de substances nocives pour l'environnement, de la pollution atmosphérique et du cycle de l'azote/l'eutrophisation. Dans la mesure où il s'agit d'un indicateur transversal, la « consommation écologiquement pondérée des ressources », qui recense les matériaux ayant un impact sur l'environnement, doit être utilisée indépendamment des quatre autres indicateurs.

Les indicateurs de l'utilisation des sols, de la consommation d'eau douce, de la pollution atmosphérique et de l'eutrophisation, ainsi que celui des changements climatiques renseignent sur les principaux impacts sur l'environnement et atteintes à la santé humaine, aux écosystèmes et aux ressources. Même s'ils n'entrent pas dans la même méthode d'évaluation, ils peuvent être utilisés conjointement (à l'exception de l'indicateur « consommation écologiquement pondérée des ressources »).

Les problématiques et impacts suivants – d'importance mondiale ou nationale – n'ont pas été abordés ou ne l'ont été que de façon marginale dans le cadre de la présente étude: acidification, écotoxicité, toxicité cancérogène et non cancérogène, radiations ionisantes (émises par des réactions nucléaires), bruit, diminution des ressources biotiques, régression des sources primaires de minéraux et d'énergie, déchets radioactifs.

L'écotoxicité, le bruit et les déchets radioactifs sont des thématiques essentielles (hormis les changements climatiques) qui ne sont pas couvertes par les indicateurs analysés dans le cadre de l'étude. La disponibilité réduite et la qualité moindre des données, ainsi que leur variabilité, constituent les principaux obstacles à l'analyse de l'impact du bruit sur l'environnement et de ses effets sur la santé humaine. Nous recommandons d'étudier ces aspects dans une phase ultérieure.

Les évolutions relatives des impacts sur l'environnement générés par la consommation suisse sur la période considérée telles qu'évaluées au moyen des indicateurs proposés dans le cadre de cette étude sont plus fiables que leurs valeurs absolues. Les valeurs absolues présentent toutefois un intérêt dès lors que des valeurs cibles sont définies.

Les indicateurs proposés permettent d'identifier si l'amélioration environnementale constatée s'explique par une amélioration réelle de la situation ou par un déplacement des impacts sur l'environnement à l'étranger. Ils permettent également de mieux évaluer les progrès accomplis par un pays pour respecter les frontières planétaires.

Content

1 Introduction

1.1 Background

As stated by Mudgal et al. (2012) in a report commissioned by the European Commission "if we continue with our current patterns of consumption, it would be inevitable to avoid irreversible damage to the planet's natural environment and jeopardise its very ability to provide these resources and the ecosystem services that we are so dependent upon" (see also Rockström et al. 2009a).

In a globalised world consumption in one country may cause important environmental impacts abroad. This is especially true for small open economies with high shares of imported goods. In Switzerland more than half of total environmental impacts of domestic consumption are related to imported goods and services (Jungbluth et al. 2011).

For this reason it is important to analyse the global environmental impacts of domestic consumption as has been done for Switzerland for the year 2005 in the pilot study of Jungbluth et al. (2011). Similar studies were performed and published quantifying the environmental impacts, resource consumption or greenhouse gas emissions of consumption in Europe and European countries (Hertwich & Peters 2009; Moll & Watson 2009; Munksgaard et al. 2001; Noorman et al. 1999; Schoer et al. 2012b; Schütz & Bringezu 2008; Tukker et al. 2006; Working Group on the State of the Environment 1999). The Federal Office for the Environment (FOEN) intends to publish time series of Swiss consumption's total environmental impacts (using a comprehensive indicator), as well as specific environmental impacts such as climate change and land use.

Nations which strive for respecting the planetary boundaries, need to address the important parts of the environmental impacts such as water use, land use/biodiversity, nitrogen and air pollutants, amongst others (Rockström et al. 2009a). Existing national environmental indicators need to be expanded beyond the national border to capture the environmental impacts caused by national consumption (see e.g. Nykvist et al. (2013, p.13)). Finally, bio-physical environmental indicators should be used to avoid weighting as far as possible.

Mugdal et al. (2012)) stated that "indicators and targets are important tools to guide, coordinate and encourage progress in the right direction" but demonstrated in their study also "that many of the available indicators desperately need to be improved or developed further."

1.2 Goal and Scope

The aim of the study is to investigate the feasibility and informative value of different life cycle indicators representing the following list of topics and environmental aspects as commissioned by FOEN:

- Water use
- Land use
- Air pollutants
- Nitrogen and
- Environmentally relevant materials

The study includes a recommendation of a set of indicators covering these five topics. In addition, this study contributes to the international discussion on such indicators. The indicators recommended should correspond to the quality requirements of environmental information of the FOEN (Schwegler et al. 2011).

1.3 General framework

According to ISO 14044, life cycle impact assessment follows a stepwise procedure (classification, characterisation, normalisation, grouping and weighting). Similarly, environmental indicators may quantify environmental damages, or an intermediate effect. With respect to climate change impacts for instance, the characterisation model can be the baseline model of 100 years of the Intergovernmental Panel on Climate Change (IPCC). The corresponding category indicator is the infrared radiative forcing (in W/m^2) and the characterisation factor is the global warming potential (GWP_{100}) for each greenhouse gas, expressed in kg CO_2-equivalents per kg gas emitted.

The GWP_{100} is a so-called midpoint indicator. It does not quantify the potential damages caused by greenhouse gases. Some environmental impact assessment methods quantify the damages of greenhouse gas emissions on human health (additional deaths due to the extension of malaria) and ecosystems (loss of biodiversity due to temperature increase). Damage oriented indicators are called endpoint indicators. Fig. 1.1 shows the general framework listing elementary flows (emissions and resource consumptions) to the left, environmental impact categories (midpoints) in the centre, and safeguard subjects (areas of protection, endpoints) to the right.

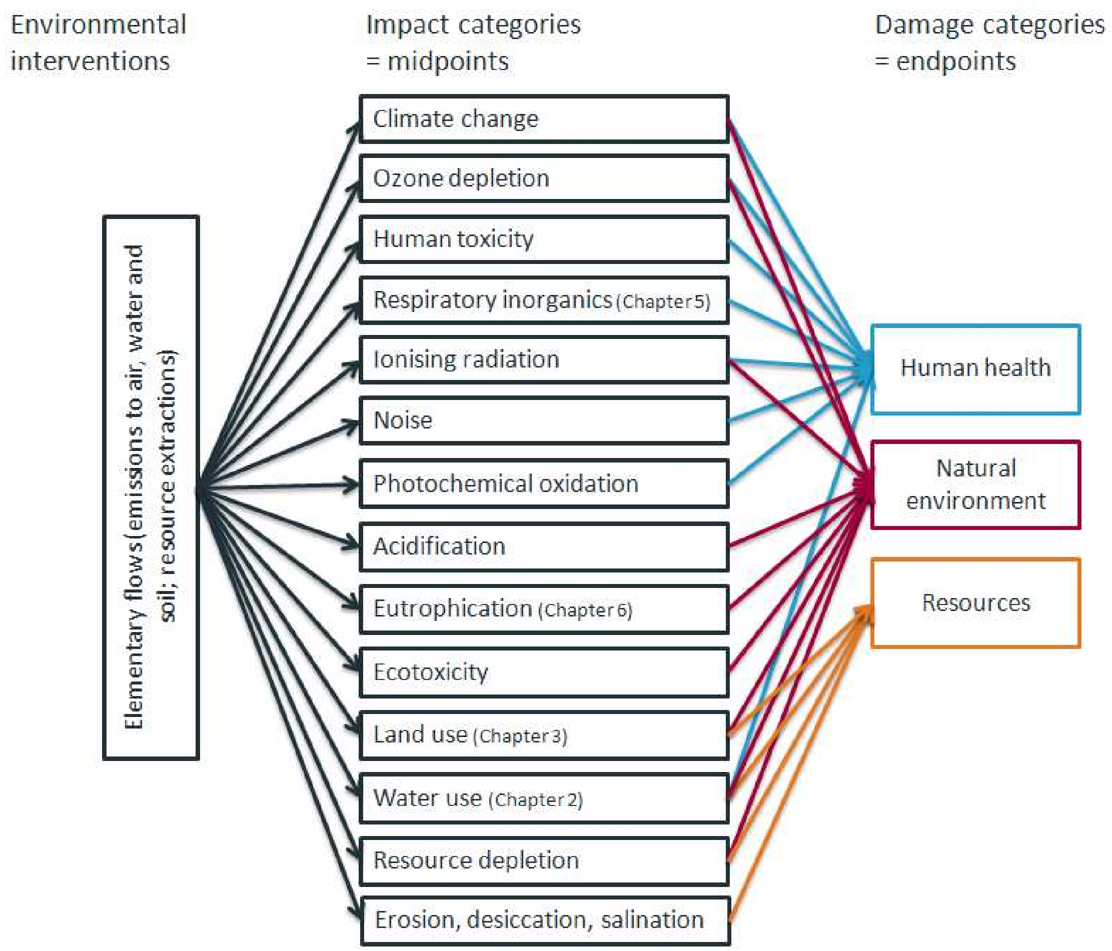

Fig. 1.1 Life cycle impact assessment environmental intervention – midpoint – damage framework[1]

The environmental indicators discussed and evaluated in this report cover the midpoints water use, land use, respiratory inorganics (and human toxicity) as well as (marine) eutrophication. The indicator on environmentally relevant material consumption is a cross-cutting indicator covering (conceptually) the entire set of environmental impact categories.

There are methodological challenges related to the development of (bio-)physical indicators, also called midpoint indicators. The categories water use, land use, nitrogen and air pollutants may each cause a variety of environmental impacts. Midpoint indicators proposed in the literature may not necessarily cover all environmental impacts. The generic term "air pollutants" is the most obvious example because this term covers pollut-

[1] FOEN uses a broad definition of the term "Natural Resources": Besides the goods such as mineral raw materials, biomass, land or water (See "Resources" in Fig 1.1), it as well includes more abstract natural resources such as clean air, biodiversity, soil fertility or climate stability.

ants like SO_2 (causing acidification), NMVOC (causing photochemical ozone), or PM10 (causing respiratory health effects). But the indicators should cover those environmental impacts that are (most) important.

The spatial and temporal variability of environmental impacts is another challenge. The environmental impacts of water use and land use are dependent on the region they occur. The environmental impacts of water use additionally depend on the season, when water is being abstracted and consumed (rainfalls may occur mainly in summer but water consumption peaks maybe during winter). Data quality and availability (regarding inventory but also impact assessment) play an important role when analysing regionalised indicators representing water use and land use.

1.4 Overarching issues

The quantification of the environmental impacts caused by the consumption of the population in a country faces several (common) challenges.

1.4.1 Variety of goods consumed

Households in developed economies consume a large variety of different goods and services (food, clothes, furniture, smart phones, toys, etc.). Besides the large variety of brands and versions available at one point in time, they also change in time quite frequently.

It will not be possible to precisely model household consumption because the level of detail of information is neither available with regard to the basket of consumption nor with regard to the environmental impacts related to all these brands and versions of all goods and services.

The quantification of the environmental impacts of national consumption and production cannot be achieved without simplifications and expert guesses. The variety of goods and services consumed are grouped into rather homogenous classes, which can then be linked to reliable life cycle inventory data. The use of interlinked and environmentally extended national economic input-output tables would be another (simplifying) approach. In both cases the level of detail decreases substantially.

1.4.2 Provenience of goods consumed

Since 2011, the Swiss trade statistics reveal the country of origin. In previous years, the trade statistics reported the countries, where the goods were cleared, which to a certain extent obscured the real countries of origin. The new statistical information helps in improving the appropriateness of transport related environmental impacts. Because information about environmental impacts of regional and national production is lacking (see Section 1.4.3) the information about the countries of origin is yet of limited use.

Furthermore, the geographic locations of the supply chains of the products[2] are hardly known nor trackable because of the complexity and dynamics of global trade.

The trade statistics do not report the season or month, when the goods and services were imported, nor do they report when exactly the imported goods were manufactured or grown (in case of food products). It will thus be difficult to determine the time period, when the environmental impacts caused by manufacturing and agricultural cultivation occurred. Indicators used to quantify the environmental impacts of national consumption and production need to be independent of time and season or represent annual averages. This is a relevant simplification, particularly with regard to water use indicators.

1.4.3 Production efficiency in country of origin

The information about the provenience of goods and services is only of little help as long as the environmental impacts caused by the production of goods and services in a particular country are not known. The level of knowledge and development with regard to life cycle assessment and life cycle inventory databases is still very diverse and, if developed at all, difficult to access.

Promising LCA database activities are currently happening in Asia (China, India, Thailand, and others) and Latin America (Costa Rica, Mexico, Brazil). However, there is still a long way to go to convince national governments about the usefulness of life cycle thinking. In some emerging economies LCA is perceived as a potential barrier to trade. Hence, efforts are needed to address and eventually dispel such scepticism towards LCA before one can think of launching national LCA activities.

1.4.4 Environmental impacts related to exports

Switzerland relies heavily on trade with foreign countries. Exporting industries such as chemicals, pharmaceuticals, watches or financial services import substantial amounts of raw materials, semi-finished products or services to produce goods which are exported to countries all over the world.

The identification of the imports dedicated for manufacture of export goods and of domestic environmental impacts caused by the production of export goods is hardly possible in a detailed way. A simplified approach using a – comparatively small and coarse – economic input-output table can help to estimate these shares.

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2 For instance, the aluminium used in a smart phone assembled in China may be sourced from Iceland, the glass cover from USA and some of the electronic components from Japan.

1.4.5 Lack of empirical verification

The quantification of environmental impacts of consumption and production in Switzerland requires simplified models. It is not possible to calibrate the model with the measurement of real environmental impacts: Life cycle based emissions and resource consumptions escape physical measurements. Thus the models and their results can only be calibrated against good scientific practice and common sense.

Different levels of sophistication and simplification exist. One main prerequisite of all approaches is a solid foundation of data of sufficient quality. Hence, sophisticated models fed with poor data does not improve the quality of the findings compared to a relatively coarse model which relies on solid data.

1.4.6 Synthesis

The evaluation of environmental indicators, as done in this study takes into account the common limitations mentioned in the previous sections. The indicators recommended are thus the result of a balance between scientific requirements and applicability. They do not have to be able to quantify differences in environmental impacts between smartphones of different brands nor different versions of the same smartphone. They should however be capable to give indications with regard to the environmental impacts of different groups of goods and services.

The indicators discussed in this study are suited to coarsely quantify impacts of Swiss consumption and production on specific environmental issues and its evolution over time. Because of limited knowledge regarding time and place and the actual production conditions of most supply chains, the numerical results provide a rough indication but no exact picture of the real environmental impacts caused. The efforts to validate the results would require a large effort and knowledge in many and diverse fields of expertise such as global trade, manufacturing efficiencies in the main producing countries, regionally differenciated environmental impacts and the like.

1.5 Overview of the contents

The report consists of five chapters describing indicators for the assessment of environmental impacts due to water use (Chapter 2), land use (Chapter 3), the consumption of materials (Chapter 6), air pollution (Chapter 4) and nitrogen fixation / eutrophication (Chapter 5).

The chapters describing the different impact indicators have a similar structure. They start with a general description of the impact pathways related to the different impact categories and used definitions and terminology.

The comparison of the different indicators starts with a short description of the indicators analysed in detail. This is followed by a quantitative comparison of the characterisation factors of the different indicators, including correlation analyses.

The overall evaluation of the different indicators according to the criteria of the "True & Fair View Study" (Schwegler et al. 2011) is divided in different subsections according to the main criteria.

The overall evaluation is followed by a short description of those indicators, that have not been analysed in detail, including the reasons for the exclusion of the indicators from the detailed analysis. Each chapter is completed with a recommendation.

The report ends with a synthesis covering the evaluation of all indicators recommended (Chapter 7).

2 Water use

2.1 Definition of water use

A range of different terms is used in the context of water use, water withdrawal, water consumption and water availability. Standard definitions of them are still under development. The definitions of some basic terms are listed in Tab. 2.1. They are used in the following methodical discussion.

Firstly, we distinguish between

- water use (which does not distinguish between the different water sources (i.e. precipitation, surface water, sea water, ground water and fossil water)
- and water availability.

Secondly, we distinguish between

- water withdrawal (the use of surface and ground water) on one hand,
- and the use of rain water on the other.

Within the use of surface and groundwater, the distinction between consumptive and non-consumptive water use is essential. Consumptive use of surface and groundwater is also called “blue water consumption”.

The consumptive water use describes the amount of water that is lost to a watershed as a result of human activities. Consumptive water use is sometimes also called “net water use” or “net water withdrawal”. The consumptive water use can be distinguished according to the type and origin of the water source.

Consumptive water use usually concentrates on the quantity of the water. The degradation of the water quality while using the water is often assessed in separate impact categories (e.g. ecotoxicity or eutrophication).

Non-consumptive water use may either be degradative (in case the quality of the water used is substantially changed before its release to the same watershed) or borrowing (in case no or hardly any change in water quality occurs). The borrowing use of water in hydroelectric power plants is usually treated separately. Current methods recommend to excluding this type of borrowing use of surface water. Turbined water may be relevant with regard to hydrological aspects such as flood and downsurge or with regard to residual water flows but not with regard to (quantitative) water use because the water is in most cases released to the same water body or at least within the same watershed.

The water footprint network introduced the category of “grey water consumption” to quantify water degradation caused by chemical pollution.

Within the use of rainwater, rainwater consumption is the main category. Whether or not to include rainwater consumption in water footprint analyses is disputed. The water footprint network quantifies the rainwater consumption in the “green water consumption" indicator. It quantifies the amount of rain fed moisture evapotranspirated by plants.

Finally, renewable water resources quantify the amount of renewable water available in a watershed or country. It includes internal renewable water resources (from precipitation) and external renewable water resources (inflows from upstream countries).

Water withdrawal and renewable water resources are two important parameters used in the water scarcity indicators described and analysed in the following.

Tab. 2.1 Definition of different terms concerning the water use and water consumption (based on Milà i Canals et al. 2009, Pfister et al. 2009, Hoekstra et al. 2011 and [3]).

Water use	Any deliberate application or utilization of water (precipitation, surface water, sea water, ground water, fossil water) for a specific purpose.
Water withdrawal (Surface and ground water use)	Water that has been removed from its source (either surface water or groundwater) for a specific use. Part of the freshwater withdrawn will evaporate, another part will return to the catchment where it was withdrawn and yet another part may return to another catchment or the sea.
Consumptive water use (blue water consumption)	The part of water withdrawn from its source for use in a specific sector (e.g. for agricultural, industrial or municipal purposes) that will not become available for reuse because of evaporation, transpiration, incorporation into products, drainage directly to the sea or evaporation areas, or removal in other ways from freshwater resources.
Non-consumptive water use	Water use which does not consume water. If ever withdrawn, almost all of the water returns to the system.
Degradative water use	Part of the water use that is released back into the same watershed but with a changed water quality (chemically or physically), e.g. from agricultural fields or cooling
Grey water consumption	Part of the consumed water, which describes the amount of water needed to dilute the load of pollutants to reach natural background concentrations. This is virtual water consumption.
Water borrowing	Part of the water use that is released back into the same water shed without a change in water quality. E.g. turbined water. The water is unrestrictedly available for further use.
Rain water use	
Rain water consumption (or green water consumption)	Part of the precipitation on land that does not run off or recharge the groundwater but is stored in the soil and evapotranspirates through plants.
Water availability	The long-term average sum of internal renewable water resources (annual flow of rivers and recharge of aquifers generated from endogenous precipitation) and external natural renewable water resources (inflows via surface water and groundwater from upstream countries). It corresponds to the maximum theoretical yearly amount of water actually available for a country at a given moment. The amount of renewable water resources typically varies within the year and also from year to year.

[3] http://www.fao.org/nr/water/aquastat/data/glossary/, accessed on February 13, 2013

2.2 Impact pathways

Fig. 2.1 shows an overview of the different cause-effect chains of water abstraction. The figure is taken from Milà i Canals et al. (2009). Water abstracted from rivers, lakes and aquifers and used in a consumptive way ("evaporative use") may change the water availability for humans and for (aquatic) ecosystems as well as the long-term water availability. These changes will affect human health, ecosystem quality and natural resources, the three main areas of protection (AoP) covered by LCA.

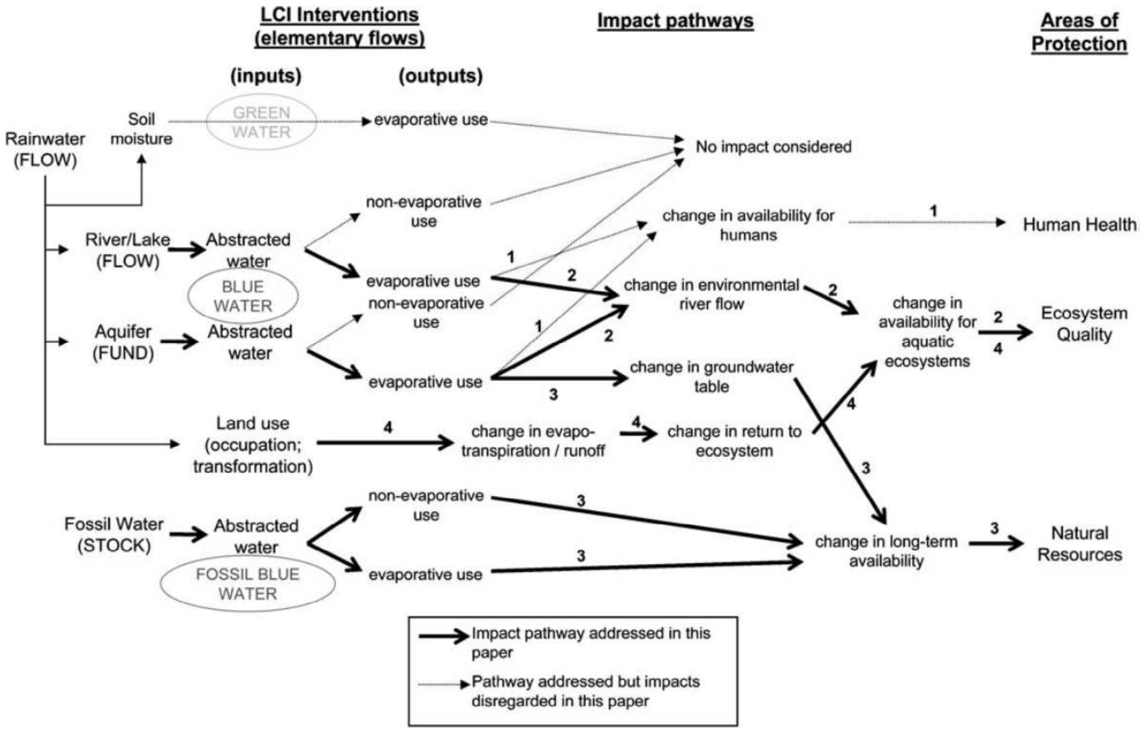

Fig. 2.1 Cause effect chains of water abstraction and use according to Milà i Canals at al. (2009)

2.3 Data sources

There are two main data sources for data on renewable water resources and water withdrawal. The first source is the FAO water database AQUASTAT (FAO 1998-2010). The AQUASTAT database provides data on water withdrawal and renewable water resources on a country level.

The second important data source is the WaterGAP2 model (Alcamo et al. 2003). The WaterGAP2 model allows the calculation of water availability and withdrawal on several spatial scales. The grid scale of the WaterGAP2 model (0.5° longitude · 0.5° latitude) supports calculations on the country and river basin level.

Data from these data sources are used by most of the indicators discussed in this report.

2.4 Selection of the indicators

2.4.1 Overview

The indicators for the assessment of water use are a refined selection of the indicators described and characterised by Kounina et al. (2012). In Kounina et al. (2012) midpoint indicators for water use impacts based on eight publications (Boulay et al. 2011, Bayart 2008, Ridoutt & Pfister 2010, Milà i Canals et al. 2009, Frischknecht & Büsser Knöpfel 2013, Pfister et al. 2009, Hoekstra et al. 2011) are compared. This selection of midpoint indicators was refined to 5 indicators. Some indicators are disregarded because they are unpublished or not easily accessible like "Water impact index" by Veolia or Bayart (2008), because they did not focus on the midpoint impact assessment (Boulay et al. 2011) or because they are very similar to an indicator analysed (Ridoutt & Pfister (2010) and Pfister et al. (2009).

The final selection analysed in this study are the indicators described by Frischknecht et al. (2013), Milà i Canals et al. (2009), Hoekstra et al. (2011) and Pfister et al. (2009).

An overview of the selected indicators is given in Tab. 2.2 and a short description of the indicators is given in the following Sections 2.4.2 to 2.4.5.

Tab. 2.2: Overview of the water indicators analysed in detail

Name	Abbreviation	Source	Section
Water scarcity indicator in the Swiss ecological scarcity method 2013	Frischknecht et al.	Frischknecht & Büsser-Knöpfel (2013)	2.4.2
Freshwater ecosystem impact according to Milà i Canals & Raskin	Milà i Canals & Raskin	Milà i Canals et al. (2009),	2.4.3
Freshwater ecosystem impact according to Milà i Canals & Smakhtin	Milà i Canals & Smakhtin		
Water footprint according to Hoekstra at al.	Water footprint Hoekstra	Hoekstra et al. (2011),	2.4.4
Water stress index according to Pfister et al.	Pfister Midpoint	Pfister et al. (2009)	2.4.5

2.4.2 Water scarcity indicator according to the Swiss Ecological Scarcity method

Within the ecological scarcity method 2013 (Frischknecht et al. 2013, Frischknecht et al. 2008, Frischknecht et al. 2006) a water scarcity indicator is proposed to assess consumptive water use. The water scarcity indicator is the squared ratio of the actual and the critical amount of water withdrawn. The critical amount of water withdrawn is set to 20 % of the available renewable water resources rate of a watershed, a country or a region. This threshold is derived from the statement in the environmental performance review report of the OECD (2003) that environmental problems related to water withdrawal start at levels above 20 % of the renewable water resources available. Six scarcity classes are proposed to simplify life cycle inventory modelling. Each individual watershed area can be assigned to one of these six scarcity classes. Main data source for renewable water resources and water withdrawal is the FAO water database aquastat (FAO 1998-2010). The calculation of the ratio on a more refined spatial scale is possible with the use of the WaterGAP2 model.

2.4.3 Freshwater ecosystem impact according to Milà i Canals

The method proposed by Milà i Canals et al. (2009) introduces the freshwater ecosystem impact as a midpoint impact category. It focuses on impacts from surface and groundwater evaporative use and land use transformation. All evaporative uses of freshwater are taken into account (including evaporated irrigation water, cooling water, evaporated water from dams and reservoirs, etc.). Milà i Canals et al. (2009) acknowledge that it can lead to an underestimation of local effects, when non-evaporative uses are considered to have no impact on freshwater ecosystem impact. The freshwater ecosystem impact is calculated with a water scarcity indicator, to be chosen between Falkenmark et al.'s water availability per capita (Falkenmark et al. 1989), Raskin et al.'s water withdrawal per availability (Raskin et al. 1997) and Smakhtin et al.'s environmental water scarcity (Smakhtin et al. 2004). In this study, we chose the latter two. They differ by the way how water resources availability is determined.

- Milà i Canals & Raskin: Raskin et al. (1997) propose to assess the water scarcity in river basins or countries based on the ratio of water withdrawal and the renewable water resources available to human and ecosystem use. They express water scarcity in river basins or countries with the ratio of total water withdrawn and the renewable water resources available. The AQUASTAT database (FAO 1998-2010) was used to calculate this ratio on the country level. The calculation of the ratio on a refined spatial scale is possible with the use of the WaterGAP2 model.
- Milà i Canals & Smakhtin: Smakhtin et al. (2004) express water scarcity in river basins by the ratio of total water withdrawn and the renewable water resources available for human use (utilisable water availability). They quantify the water requirements of the ecosystems in a river basin by estimating the environmental water requirements (EWR) for all world river basins. They subtract the EWR from the total renewable water resources available to quantify the utilisable water availability. The calculation is done on the refined spatial scale of the basin level and requires the use of the WaterGAP2 model. Together with a GIS software average water scarcities of countries can be calculated. Calculations and updates of the characterisation factors require the assistance of the authors.

2.4.4 Water footprint according to Hoekstra et al.

The water footprint according to Hoekstra et al. (2011) is a life-cycle based approach to quantify the water use caused by the production of different consumer goods and services.

In order to quantify the water footprint of products, the cumulative consumptive use of green and blue water and the cumulative grey water use along the whole life-cycle are quantified. Green and blue water consumption and grey water use are added up without characterisation, i.e. without considering regional water scarcities; the cubic meters are simply added up. The three indicators (green, blue and grey water footprint of products and services) are displayed separately.

While they abstain from using water scarcities when establishing *product* water footprints, Hoekstra et al. (2011) offer blue water scarcity factors on a regional (water basin) level. They use the ratio of consumptive water use to total renewable water resources available in a river basin to establish scarcity indicators. Water scarcity reaches 100 % in case 20 % of the renewable water resources available are withdrawn for consumptive use (Hoekstra & Mekonnen 2011). The scarcity indicators are published on a monthly and annual basis for the world's major river basins.

Data on the consumptive blue and green water use in river basins or countries are not available in the major data sources (AQUASTAT and WaterGAP2). Calculations and updates of the characterisation factors (scarcity indicators) would require the assistance of the authors.

2.4.5 Water stress index according to Pfister et al.

The midpoint method developed by Pfister et al. (2009) assesses the impacts of freshwater consumptive use. The midpoint impact category indicator they propose is an adapted water scarcity index. This index uses a modified withdrawal to availability ratio, which differentiates watersheds with strongly regulated flows. A variation factor is introduced to account for flow regulation in the different basins. It is derived from the standard deviation of the precipitation distribution. The variation factor takes into account insufficient water storage capacities or lack of stored water in case of increased water scarcity during periods of drought.

The calculation of the characterisation factors has to be done on the watershed or grid scale with the WaterGAP2 model. They are also available on a country scale. Calculations and updates of the characterisation factors (water scarcity indexes) require the assistance of the authors.

2.4.6 Summary

All indicators except Hoekstra et al. (2011) are principally based on the ratio of the amount of water withdrawn and the renewable water resources available. Hoekstra & Mekonnen (2011) use the ratio of consumptive water use and the renewable water resources available. However, they do not apply the scarcity ratio in their water footprint analyses of products and services.

All indicators except Hoekstra et al. (2011) but including Hoekstra & Mekonnen (2011) can be expressed in scarcity-weighted amounts of water (expressed in m^3 water-eq) using the scarcity-weighted water consumption in one region (country) as the reference substance. The water footprint according to Hoekstra et al. (2011) includes no characterisation of the water flows when quantifying product water footprints and uses the actual physical amounts of water, expressed in cubic meters.

2.5 Comparison of the characterisation factors

Fig. 2.2 shows the comparison of the characterisation factors of water scarcity indicators according to Frischknecht et al. (Frischknecht & Büsser Knöpfel 2013), Milà i Canals & Raskin (Milà i Canals et al. 2009, Raskin et al. 1997), Milà i Canals & Smakhtin (Milà i Canals et al. 2009, Smakhtin et al. 2004), Pfister Midpoint (2009) and to the three endpoints human health, ecosystem health and resources, and the total environmental impacts according to Pfister et al. (2009) using the Eco-indicator 99 method.

The characterisation factors are normalised with the characterisation factor of Denmark[4] in order to enable the comparison of the country specific differences. The figure shows the dimensionless values for all countries, for which characterisation factors are available relative to the characterisation factor of Danish water consumption.

We have used a logarithmic scale in order to be able to show the whole range of the values of the characterisation factors. There is a huge difference between the lowest and the highest characterisation factors within one indicator, representing regions with no to lowest water stress and regions with extreme water stress, respectively. In case of the indicator according to Frischknecht et al. the highest characterisation factor is 10^{11} times higher than the lowest. The indicator according to Milà i Canals & Smakhtin shows a similar range of variation of 10^{10} between the lowest and the highest characterisation factors. The range between the highest and the lowest characterisation factor is 10^6 in case of Milà i Canals & Raskin and about 100 in case of Pfister et al. (2009). This large spread of factors within some of the water stress indicators may tend to overestimate the differences in environmental impacts caused by water use. The correlation analyses between water stress indexes and impacts on resources, human health and ecosystems show to what extent this might be the case (see Tab. 2.3).

The scale of the water scarcity indicator according to Pfister et al. (2009) is intentionally (by conversion) limited between the values 0.01 and 1, whereas the other indicators have no fixed limitations.

Pfister endpoint total and Pfister endpoint ecosystem quality show a very similar pattern since the damages on ecosystems contribute about three quarter to the total damages.

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4 Denmark is chosen because the Danish withdrawal to availability ratio corresponds to moderate water stress (withdrawal to availability ratio for Denmark 11.5 %) Environmental problems related to water withdrawal start at levels above 20 % according to the OECD (2003).

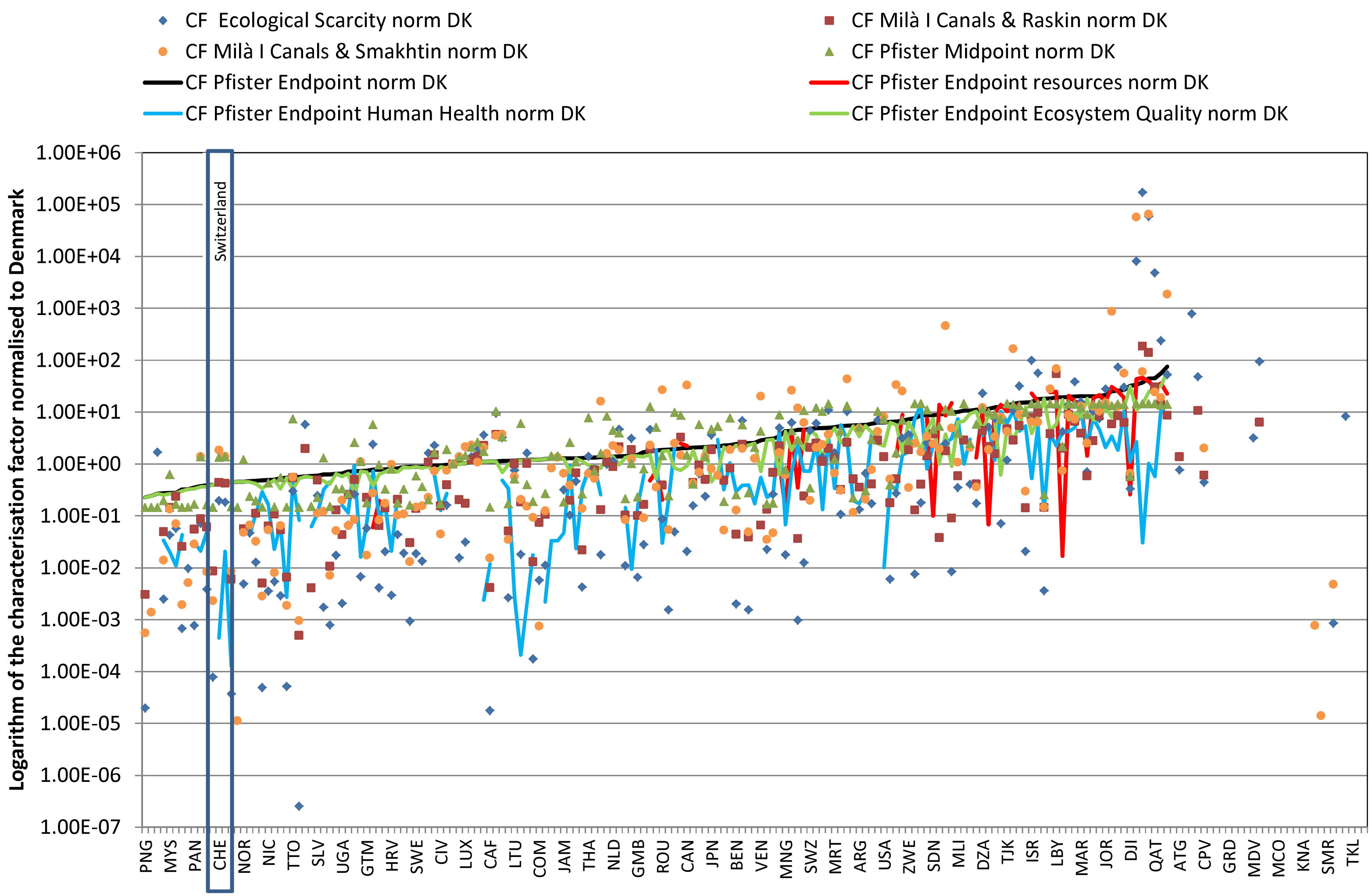

Fig. 2.2 Comparison of the characterisation factors of the different indicators normalised with the characterisation factor of consumptive water use in Denmark on a logarithmic scale

Tab. 2.3 shows the correlation coefficients of the different indicators analysed and the endpoint indicators of the total environmental impacts and on the different safeguard subjects (human health, ecosystem quality and resources) according to Pfister et al. (2009) based on a regionalisation on country level and, for the approaches Frischknecht et al. and Pfister midpoint, on a river basin level. The results of the correlation analyses give an indication to what extent midpoint indicators are similar to each other and whether or not a midpoint indicator is a suitable proxy for damages on resources, human health, ecosystem quality or overall environmental impacts.

The correlation between the characterisation factors of the different indicators differs heavily. Frischknecht et al. shows very good correlation to Milà i Canals & Raskin but only low correlation with Milà i Canals & Smakhtin and Pfister midpoint. Pfister midpoint shows little correlation with any of the other indicators analysed.

Tab. 2.3 Correlation coefficient of the country specific characterisation factors of the different water use indicators analysed with regionalisation on country level (white background) and on watershed level (background in light grey), correlation coefficients above or equal to 0.50 are highlighted with dark grey colour

Correlation coefficient	Frisch-knecht et al.	Milà i Canals & Raskin	Milà i Canals & Smakh-tin	Pfister Mid-point	Pfister End-point total impacts	Pfister End-point Re-sources	Pfister End-point Human Health	Pfister End-point Ecosys-tem Quality
Regionalisation on country level (own calculations)								
Frischknecht et al.	1.00	0.94	0.26	0.21	0.32	0.50	-0.04	0.20
Milà i Canals & Raskin		1.00	0.57	0.33	0.47	0.64	0.01	0.32
Milà i Canals & Smakhtin			1.00	0.21	0.35	0.46	0.02	0.24
Pfister Mid-point				1.00	0.65	0.72	0.62	0.43
Regionalisation on watershed level (based on Pfister et al. (2009), supporting information, p. S18-S19)								
Frischknecht et al.					0.58	0.90	0.35	0.19
Pfister Mid-point					0.51	0.73	0.42	0.19

Pfister midpoint shows the best correlation with the endpoints according to Pfister et al. (2009), followed by Milà i Canals & Raskin.

Pfister et al. (2009 , supporting information, p. S18-S19) assessed the correlation of the environmental damage on human health, ecosystem quality and resources expressed in Eco-indicator 99 points and their water use midpoint indicator as well as the water use indicator based on the ecological scarcity method 2006. The correlation analysis is performed on a watershed basis. It reveals that both indicators show a good correlation relative to the damage to resources (Pfister et al.: RR = 0.73 and Frischknecht et al.: RR = 0.90) and a moderate correlation relative to the overall environmental impacts (Pfister et al.: REI = 0.51 and Frischknecht et al.: REI = 0.58). The correlation of the indicators relative to damages on ecosystem quality and human health are very low (both indicators: REQ = 0.19) and low (Pfister et al.: RHH = 0.42 and Frischknecht et al.: RHH = 0.35), respectively. The two indicators are thus most suited to cover the resource depletion aspect of consumptive water use.

Frischknecht et al., Milà i Canals & Raskin, and Pfister midpoint are able to quantify the stress on water resources in a rather reliable way. Pfister midpoint turns out to be a good proxy indicator for damage on human health and for total environmental impacts as well, whereas Frischknecht et al. show a high correlation to damages on resources.

There is a large difference in correlation of Frischknecht et al. and the damage assessment according to Pfister et al. (2009). On a river basin level the correlation of the indicator according to Frischknecht et al. with damages on resources is 0.9 whereas it drops to 0.50 on the country level. This is possibly due to a difference in aggregation. While the country specific indicators of Frischknecht et al. are based on country averages, the country specific environmental damages according to Pfister et al. are an integration of damages quantified on a river basin level.

Tab. 2.4 shows the comparison of characterisation factors of selected countries, which have a high importance regarding the Swiss trade balance, relative to the characterisation factor of Switzerland.

The relative characterisation factors differ by one to two orders of magnitude. Due to its squared scarcity function, the indicator of Frischknecht et al. shows a significantly higher spread as compared to, for instance, Pfister midpoint, who limits the scarcity index between 0.01 and 1.0. The sequence of countries shown by all indicators except Milà i Canals & Smakhtin is similar to the sequence of countries shown by the indicator Pfister Endpoint with Israel being the country with the highest impacts and Switzerland being the country with the lowest impacts.

There are minor deviations in the ranking of one or two ranks like China being rated higher than Spain in case of Pfister Endpoint but not in case of Pfister midpoint and Frischknecht et al.

Tab. 2.4 Country specific characterisation factors of selected countries with a high importance for the Swiss economy. The factors are shown relative to the characterisation factor of Switzerland.

Country	Frischknecht et al.	Milà i Canals & Raskin	Milà i Canals & Smakhtin	Pfister Midpoint	Pfister Endpoint	Ranking
Israel	504.8	17.7	3.5	10.8	38.8	1
India	56.0	6.5	90.6	10.5	35.8	2
China	15.9	n.a.	13.7	5.2	17.1	3
Spain	35.5	6.5	2.3	7.7	15.7	4
Italy	23.6	4.8	1.0	3.0	3.5	5
Netherlands	5.7	2.0	1.2	3.3	3.4	6
Germany	18.4	5.2	1.1	1.3	2.8	7
Switzerland	1.0	1.0	1.0	1.0	1.0	8

2.6 Evaluation of the selected water use indicators

2.6.1 Overview

Tab. 2.5 shows the summary of the evaluation of the five indicators analysed according to the scheme of the "True & Fair View" study (Schwegler et al. 2011). A detailed evaluation is shown in Appendix A.

The main differences between the indicators analysed occur in the environmental relevance, transparency, data availability and complexity of the implementation.

Tab. 2.5 Comparison of the water use indicators according to the “True & Fair View” requirements; +: good performance; -: bad performance; +/-; both good and bad performance

Topic	Water use				
Indicator	Frischknecht et al.	Milà i Canals & Raskin	Milà i Canals & Smakhtin	Water footprint Hoekstra	Pfister Midpoint
Environmental relevance	+	+	+/-	- [1)] + [2)]	+
Focus on the overall picture	+	+	+	+	+
Reliability	+	+	+	+	+
Transparency	+	+	+/-	+/-	+/-
Comprehensibility / communi-cability	+/-	+/-	+/-	+/-	+/-
Coherence and Comparability	+/-	+/-	+/-	+/-	+/-
Availability of information: Data availability and quality	+	+	+/-	+/-	+
Timeliness (up-to-date informa-tion)	+	+	+	+	+
Ease of implementation	+/-	-	-	+	+/-

[1)] water footprint of products

[2)] blue water scarcity index

2.6.2 Environmental relevance

Water use midpoint indicators cannot reflect the complexity of possible environmental impacts due to water use. Hence, all indicators analysed are proxy indicators which try to capture the multi-faceted impacts as good as possible.

All the indicators analysed except Hoekstra et al. (2011) but including Hoekstra & Mekonnen (2011) rate the water scarcity in specific locations based on the ratio of the amount of water withdrawn and the renewable water resources available. The scarcity based indicators best reflect the impacts caused on natural resources as shown by the correlation analyses. Hoekstra & Mekonnen (2011) rate the water scarcity in specific locations based on the ratio of the amount of water consumed and the renewable water resources available. However they do not apply these water scarcities when calculating water footprints of products and services.

The approach of Milà i Canals & Smakhtin takes into account the water requirements of ecosystems. However, the correlation analysis shows that the indicator does not address impacts on ecosystems appropriately.

The approach of Pfister et al. adjusts the withdrawal to availability ratio with a factor reflecting the storage capacities in the different basins. This leads to improvements of the characterisation factors regarding the impacts of multiannual events like droughts. On a country level this leads to improved correlation between their indicator and damages on resources and human health.

2.6.3 Focus on the overall picture

The focus on the overall picture is different depending on the indicator analysed. The approach of *Frischknecht et al.* is a good proxy indicator for stress on water resources. The indicator is adjustable to any level of regionalisation. The method of *Milà i Canals and Raskin* does not focus on one particular area of protection. Their indicator is adjustable to any level of regionalisation. The method of *Milà i Canals and Smakhtin* focuses on the water needs of ecosystems. Their indicator does not particularly well reflect damages on ecosystems though. Their indicator is adjustable to any level of regionalisation. The *water footprint* according to Hoekstra et al. does not focus on a specific area of protection and does not account for water scarcity. Thus it does not require regionalised information. The method *Pfister midpoint* does not focus on a specific area of protection but correlates best with stress on water resources. It uses a regionalisation on the 0.5° grid cell level but can be adjusted to any level of regionalisation.

2.6.4 Reliability

All indicators presented have a solid scientific basis and are published and reviewed. The calculations do not include value choices but assess the scarcity of water in different countries or river basins. However, the concepts of the indicators themselves include value choices (e.g. in the approach of Milà i Canals & Smakhtin: assure that 100 % of the water demand of ecosystems is covered).

The indicator according to Frischknecht et al. is recommended by the DG-JRC (Hauschild et al. 2011, p. 100) and proposed for the quantification of Product Environmental Footprints in Europe (European Commission 2012). The indicator of Pfister has a high standing in the LCA community (both academia and industry).

2.6.5 Transparency

The transparency of the indicators analysed is generally high. The characterisation factors based on Frischknecht et al., Milà i Canals & Raskin and Hoekstra et al. are easily calculated and reproduced. The characterisation factors based on Pfister et al. and Milà i Canals & Smakhtin are more complex to calculate and thus are less easily reproducible. Data on water scarcity indexes according to the approach of Hoekstra et al. are published on the level of river basins (monthly and annual averages, see Hoekstra & Mekonnen (2011).

2.6.6 Comprehensibility (Understandability /communicability)

The communicability is different depending on the indicator analysed. The physical unit of the water footprint according to Hoekstra using a water volume is easy understandable. However, since there are three different water uses (blue, green and grey), the difficulty in communication is strongly increased. Communicability of all the other indicators is easier, since the results of all other indicators can be expressed in one number in m^3 water equivalents. The virtuality of a water equivalent is, however, a bit more difficult to understand.

2.6.7 Coherence and comparability

The indicators analysed show a high level of coherence and comparability. All indicators prove to be extendable on different spatial scales like watersheds or countries, given that the necessary information is available.

When looking at the comparability of time series, all indicators except the product water footprint according to Hoekstra are based on characterised water equivalents, which complicate the comparison of the time series, if there is a change in the characterisation factors. The indicators of Milà i Canals & Smakhtin and Pfister midpoint do not need more frequent updates because the additional data on EWR and flow regulation do not change significantly in short time.

Comparability between the characterisation factors of one indicator on the country or watershed level is given because consistent data source are used for the calculation of each indicator. However, comparability between the different indicators is not given because different data sources are used depending on the indicator (AQUASTAT, WaterGAP2, and other)

2.6.8 Availability of information (data availability and quality)

The data needed for the indicators Frischknecht et al., Milà i Canals & Raskin and Pfister midpoint are readily available on the country level and have a high quality as they are consolidated by FAO and published via the AQUASTAT database. The calculation of these indicators on the basin level is feasible as well but requires the use of the WaterGAP2 model and GIS software.

The additional data on EWR needed for Milà i Canals & Smakhtin and the water scarcity indicator values developed by Hoekstra et al. are only available on river basin level.

2.6.9 Timeliness (up-to-date information)

Data used to calculate the indicators are rather recent (within the last 10 to 15 years). Data in the WaterGAP2 model are somewhat older. In general averages covering several years or decades are used. Data on the available water resources on country level are available for the year 2009 through the AQUASTAT database. A little bit less recent withdrawal data between 2000 and 2005 are available for most of the countries (FAO 1998-2010). These data sources can be used for the indicators Frischknecht et al. and Milà i Canals & Smakhtin. However, since AQUASTAT only provides data on the country level, the calculation of basin specific characterisation factors is not possible with the AQUASTAT database. Characterisation factors using this most recent data will be published for the approach of Frischknecht et al. Data quantifying the water scarcity in major river basins according to Hoekstra et al. cover a ten years period from 1996 to 2005.

The data in the WaterGAP2 model relates to the climate normal period from 1961 to 1990 and was used for the calculation of the indicators according to Milà i Canals & Smakhtin and Pfister midpoint. Data on the EWR used by Milà i Canals & Smakhtin are from the year 2004 (Smakhtin et al. 2004) and data on the flow regulation used by Pfister midpoint are from the year 2005 (Nilsson et al. 2005).

2.6.10 Ease of implementation

The implementation of all the indicators, except for Hoekstra et al. into LCA background data is rather complex for two reasons. Firstly, the water use indicators are supposed to be applied on the consumptive use only. Secondly, water use indicators should be applied on regionalised inventory data.

Consumptive water use: Consumptive water use includes all water withdrawn and released either in other water sheds or evaporated or water embodied into products. Background databases such as ecoinvent need to be complemented with elementary flows quantifying the amounts evaporated and exported (to other watersheds) and the amounts embodied. The characterisation factors are then applied on these amounts only.

Regionalised inventory data: The ecoinvent database does not yet provide regionally differentiated information. To enable the use of regionalised characterisation of water use, regionalised water use data have to be established. The indicator of Frischknecht et al, provides a more simplified classification in only six water scarcity classes. This rough approximation of regionalisation reduces the effort needed to adjust current background inventory data.

2.7 Further indicators, not analysed in detail

2.7.1 Boulay

The midpoint proposed by Boulay et al. (2011) is the scarcity parameter of their endpoint model for damage on human health. This scarcity is distinct for different water categories, and is zero for water of low quality and for seawater. For surface water, the parameter is based on the ratio of surface water consumed and a “statistical low flow” amount which accounts for seasonal variation (Döll 2009). For groundwater, the parameter is based on the groundwater consumed and the availability of groundwater resource. These ratios are then adapted to include the local availability of water of a certain quality based on data from GEMStat database (UNEP 2004). This midpoint indicator is determined at the watershed level.

This indicator is not analysed in detail because of the focus on the endpoint assessment, its relatively complex nature and missing information for a quantitative comparison of the method.

2.7.2 Bayart

Bayart (2008) developed a method to evaluate the impact of water deprivation for human use. He developed characterisation factors which vary according to water scarcity and water quality. Compensation scenarios (e.g. waste water treatment or desalination) are also taken into account but their impact is not explicitly calculated. The model, implemented in two softwares (Excel and Analytica), is not available.

This indicator is not analysed in detail because of limited availability of information needed for a quantitative comparison of the method and its relatively complex nature.

2.7.3 Veolia water impact index

The Water Impact index is a simplified metric for assessing impacts on water use. This indicator aims to address the modification of freshwater resource availability due to human activities. It allows evaluating how other water users (both humans and ecosystems) would potentially be deprived from this resource.

Water flows abstracted from, or released into the environment are weighted by a water scarcity index of the location where the water is used (e.g. Pfister's water stress index); and by a quality index. The latter is calculated as a ratio between a reference concentration based on Environmental Quality Standards for a specific pollutant and the actual concentration of this pollutant in the water flow. In the case of multiple pollutants, the quality index is calculated according to the most penalizing pollutant. If, for all pollutants considered, the concentration is below the reference concentration, the Quality Index is set to 1 (water quality reaching environmental requirements).

Consumptive use is calculated by quantifying the water withdrawal (positive, leading to an increase of the Water Impact Index by reducing the water availability) and the water discharge (negatively, leading to a decrease of the Water Impact Index by increasing the water availability).

This indicator is not analysed in detail because water quality can hardly be quantified in a generic way. Furthermore no reviewed publication was available.

2.7.4 Ridoutt and Pfister

In the publication of Ridoutt & Pfister (2010), characterisation factors of the water stress index according to Pfister et al. (2009) are applied on blue water consumption and grey water according to Hoekstra et al. (2011).

A detailed comparison of the indicators according to Ridoutt & Pfister (2010) and Pfister et al. (2009) would lead to redundant results because both papers apply the same water stress index. The water stress index according to Pfister et al. (2009) was selected being the original publication.

2.8 Adjustments Berger

Berger et al. (2012) have made suggestions to complement and improve existing approaches to assess water use impacts.

They suggest the inclusion of the basin internal evaporation recycling as an additional parameter, when assessing consumptive water use. They suggest to square the denominator in the withdrawal to availability ratio in order to consider the sensitivity of an additional water consumption (1'000 m^3 consumed in a river basin with only 100'000 m^3 of renewable water resources available is more severe as compared to the same amount consumed in a river basin with the same withdrawal to availability ratio but with 1'000'000 m^3 of renewable water resources available). They suggest the implementation of an adjustment factor for ground water stocks, which would allow for a consumption of more than the annual average amount of renewable water resources available. They suggest to introduce a sensitivity index based on the population density in order to consider the vulnerability of the population and the ecosystems.

Furthermore, they suggest the use of a logistic function in order to fit the values of the characterisation factors (water scarcity factors) in the range between 0.01 and 1 and the use of threshold values for areas with low rainfall and saline groundwater to complement the sensitivity index (which is based on population density).

Being conceptual ideas only, these suggested adjustments are not analysed in depth.

2.9 Recommendation

None of the midpoint indicators analysed is capable to completely represent the multifaceted impacts of consumptive water use. The indicators Pfister midpoint and Frischknecht et al. prove to be the best proxy indicators, in particular with regard to damages on water resources.

We recommend the Pfister midpoint indicator. This indicator shows a relatively higher correlation with impacts on human health and ecosystems on a country level as compared to the indicator of Frischknecht et al.. Furthermore, the midpoint indicator of Pfister has a high standing in the LCA community (both academia and industry).

3 Land use

3.1 Impact pathways of land use

Fig. 3.1 shows the different impact pathways of land use. Land use may affect land competition, ecosystem services such as the biotic production potential (net primary production (NPP)), soil organic matter content (SOM), biodiversity (species richness) and land competition.

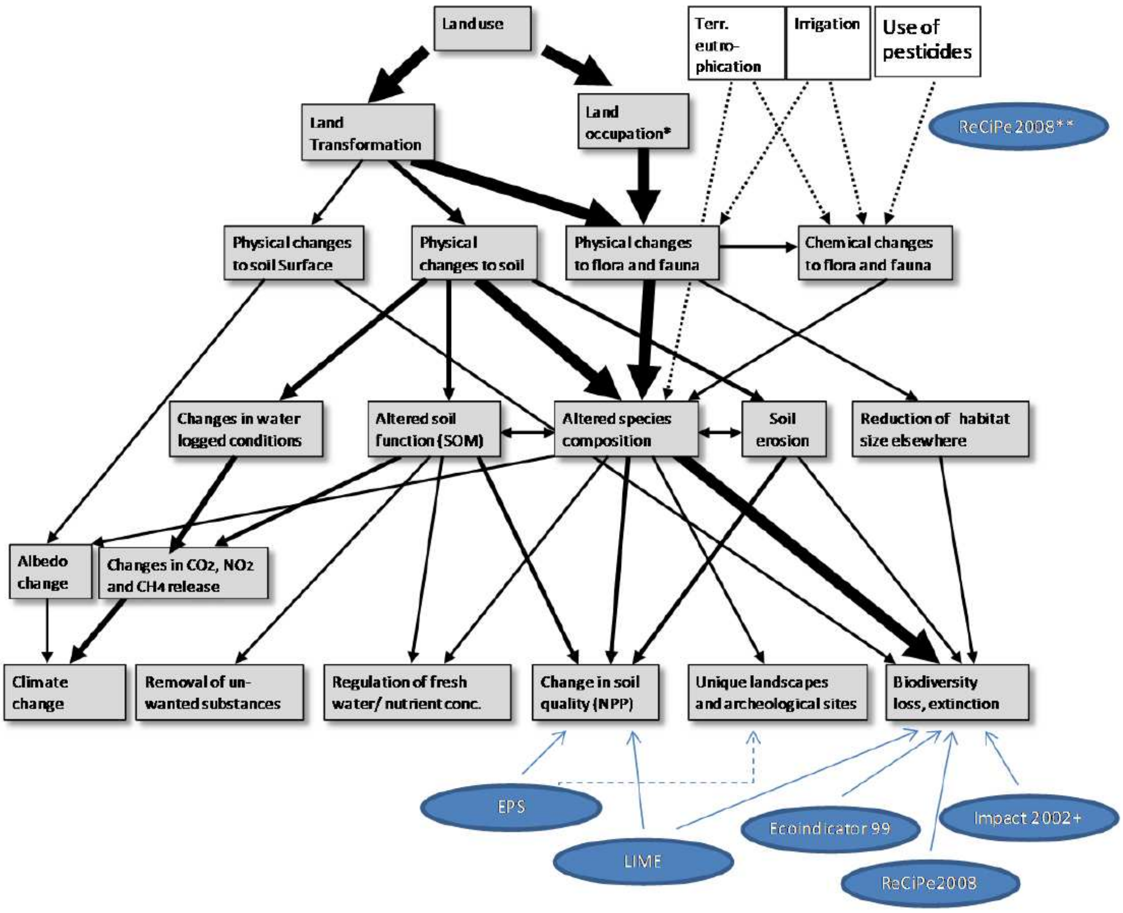

Fig. 3.1 Impact pathways of land use according to Hauschild et al. (2011)

Tab. 3.1 shows the two main safeguard subjects affected by land use: ecosystem services and biodiversity (Milà i Canals et al. 2007b). The impacts of land use on biodiversity can either be quantified by the amount of potentially affected or disappeared fractions of species, by the share of threatened species or by red listed species. Land and soil provide many different ecosystem services. Two often addressed safeguard subjects are the biotic production potential and the ecological soil quality. Finally, the actual land demand is reflected by a land competition indicator.

Tab. 3.1: Safeguard subjects affected by land use and indicators addressing the impacts; according to Milà i Canals et al. (2007b) and own additions

	Safeguard subject	Possible indicators	Level
Biodiversity	Biodiversity (Natural environment)	PDF (Potentially disappeared fraction of species) PAF (potentially affected fraction of species)	Endpoint
		Share of threatened vascular plant species	Midpoint
		Red-listed species	Midpoint
Ecosystem services	Biotic production potential (Natural resources)	Deficit of soil organic matter	Midpoint
		Eroded soil	Midpoint
		Average potential productivity [1])	
	Ecological soil quality (Natural environment)	Combination of indicators describing soil properties like pore volume, soil organic matter, microbial activity etc	Midpoint
Actual land demand		Land competition (unweighted) [2])	Midpoint

[1]) used in the ecological footprint

[2]) used in Lugschitz et al. and ReCiPe midpoint

3.2 Land occupation and transformation

Land use impacts can be divided into two major sub processes: land occupation and land transformation. Fig. 3.2 shows an illustration of land transformation, land occupation and restoration as well as the development of land quality in the course of time.

Land occupation refers to the use of a land area for a certain time period (t_1 to t_2). Land occupation is measured in area-time-units (e.g. m^2*year) representing a certain area (m^2) used for a certain time period (year).

Land transformation describes the change of a land area from one type to another one (e.g. from forest to cropland at time t_1 in Fig. 3.2). The quality may be lowered from level A to level B because of this change in use. Land transformation is measured as an area (e.g. 1 m^2 of forest transformed to cropland).

When land used for a specific purpose is abandoned (time t_2 in Fig. 3.2), the land will be restored (either passively or actively) until it reaches a new equilibrium (level D). The restoration time varies between years, decades and centuries, depending on the severity and reversibility of the initial transformation.

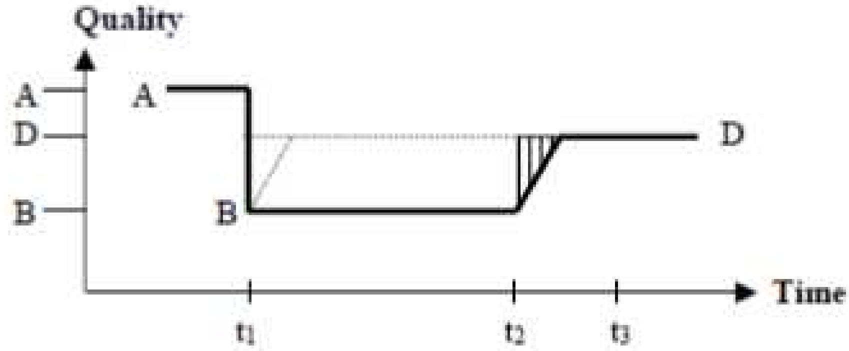

Fig. 3.2 Land quality before, during and after a human activity in the time interval $t_1 - t_2$; Figure according to Weidema et al. (2001)

There are still severe methodological problems related to the quantification of land transformation. This is mainly due to missing knowledge about realistic restoration times and due to assumptions needed with regard to the time period of land occupation which follows (and antecedes) a land transformation. This time period is important to relate the land transformation impacts to the activities taking place during occupation.

Finally it is also important to be aware that land occupation may cause land use change indirectly through land competition.

Because of these methodological uncertainties we limit the selection of indicators to those representing land occupation.

3.3 Selection of the indicators

3.3.1 Overview

The indicators for the assessment of land use are a refined selection of the indicators described and characterised by Hauschild et al. (2011) (Weidema & Lindeijer 2001; Baitz 2002; Milà i Canals et al. 2007c; Goedkoop et al. 2009) and the indicators proposed by the FOEN (Feldwisch et al. 2006; Frick 2012; Lugschitz et al. 2011; Roth et al. 2010; Staub et al. 2011) and other common indicators developed by de Baan & Olson (de Baan et al. 2012; Frischknecht & Büsser Knöpfel 2013; Olson 2001), Haberl et al. (2012) and Wackernagel et al. (2005).

The selection is based on criteria like coverage of different impacts (on biodiversity and on different ecosystem services), the prevalence of the indicator in administrations and the scientific community, the accessibility of data and compatibility with the consumption perspective followed by the FOEN. The reasoning behind the selection is described in more detail in Subchapter 3.5.

The indicators described by Lugschitz et al (2011), Wackernagel et al. (2005), Köllner (Frischknecht et al. 2008; Köllner 2001), de Baan & Olson (de Baan et al. 2012;

Frischknecht & Büsser Knöpfel 2013; Olson 2001) and Milà i Canals et al. (2007c) are analysed in detail.

An overview of the selected indicators is given in Tab. 3.2 and a short description of the indicators is given in the following Sections 3.3.2 to 3.3.6.

Tab. 3.2: Overview of the land use indicators analysed in detail

Name	Abbreviation	Source	Impact pathway / indicator
Land demand	Lugschitz	Lugschitz et al. 2011	Land competition
Ecological footprint	Ecological foot-print	Wackernagel et al. 2005	Biotic production potential average potential productivity
Köllner implemented in ecological scarcity 2006	Köllner	Köllner et al. 2012;Frischknecht et al. 2008	Biodiversity relative plant species richness
Land use impacts on bio-diversity implemented in ecological scarcity 2013	De Baan & Olson	de Baan et al. 2012;Olson 2001;Frischknecht & Büsser Knöpfel 2013	Biodiversity relative species richness
Land use impacts on soil quality	Milà i Canals	Milà i Canals et al. 2007c;Milà i Canals et al. 2007a	Biotic production potential deficit of soil organic matter

3.3.2 Land demand according to Lugschitz

Lugschitz et al. (2011) apply a multi-regional input-output (MRIO) analysis to calculate the direct and indirect (embodied) land demand of products consumed in Europe. MRIO analysis is a methodology to assess the international environmental consequences of regional consumption activities. It combines economic data (i.e. data on the sectoral structure of economies linked via international trade data) with physical information (e.g. the global land use for the production of different commodities). The model captures the upstream impacts on global land use induced by a country's consumption of goods. Land demand is quantified in m^2, and this indicator does not distinguish between different land use types, nor biomes.

The indicator used in Lugschitz et al. is similar to land competition according to CML (Guinée et al. 2001a; Guinée et al. 2001b) or the ReCiPe midpoint land occupation (Goedkoop et al. 2009).

3.3.3 Ecological Footprint according to Wackernagel

The ecological footprint is defined as the biologically productive land a population requires to produce the resources it consumes. The ecological footprint calculates the biologically productive area needed to sustain a population's socio-economic metabolism.

In this analysis we only take the direct land use component of the ecological footprint into account. The indirect land use to absorb carbon dioxide generated by non-renewable energy consumption is not considered, since the global warming potential is already taken into account by a separate indicator and since the focus of this analysis lies on the direct impacts of land use.

Nine different biologically productive areas are considered (primary cropland, marginal cropland, pasture, forest, fisheries, built-up area, hydropower area and forest for carbon sequestration). Built-up area is assumed to be located mostly on primary cropland.

The data used to calculate the average potential productivity is mainly based on the FAOSTAT database (FAO 2011) and complemented with data from other FAO databases. Productivity in the context of the ecological footprint does not refer to a rate of biomass production, such as net primary production (NPP). Rather productivity is the *potential* to achieve maximum agricultural production at a specific level of inputs (see next section). Thus one hectare of highly productive land is equal to more global hectares than one hectare of less productive land.

3.3.4 Land use according to Köllner

The method according to Köllner (2001) implemented in the ecological scarcity method 2006 (Frischknecht et al. 2008) quantifies land occupation impacts on biodiversity. The approach distinguishes 57 different land use types (urban, agricultural, forests and others). Plant species richness of different land use types is compared to a reference situation in order to derive relative changes in species richness. The relative species richness is derived with a nonlinear damage effect function. The number of species is based on the national Biodiversity Monitoring Switzerland (BDM 2004) and several further information sources. The impact category indicator is called ecosystem damage potential (EDP).

3.3.5 Land use impacts on biodiversity according to de Baan & Olson

The indicator proposed by de Baan et al. (2012) addresses land occupation impacts, quantified as a biodiversity damage potential (BDP). Species richness of different land use types is compared to (semi-)natural regional reference situations. This allows to calculate relative changes in species richness for 14 different biomes and for a global average[5].

Data on multiple species groups were derived from a global quantitative literature review documented in the Globio3 data base (Alkemade et al. 2009) and national biodiversity monitoring data from Switzerland (BDM 2004). Differences across land use types, biogeographic regions (i.e., biomes), species groups and data sources were statistically analysed. The relative species richness is derived with a linear damage effect

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[5] The species considered for the calculation of the relative species richness are arthropods and other invertebrates, birds and other vertebrates, vascular plants and mosses.

function. The indicator proposed by de Baan et al. (2012) is a further development of the indicator developed by Köllner (2001).

The approach uses the biome classification of Olson et al. (2001). Frischknecht et al. (2013) extend the approach and establish biome specific characterisation factors which are summable. For that purpose the characterisation factors of land use in the different biomes are referred to the actual average plant species richness in the different biomes, which is reported in Kier et al. (2005). This is a rough assumption which is supported by experts in this area[6].

The method provides characterisation factors for 8 different land use types (unused forest/grassland, secondary vegetation, used forest, pasture/meadow, annual crops, permanent crops, agroforestry and artificial areas). These 8 different land use types reported in de Baan et al. (2012) are further differentiated using information from Köllner & Scholz (2007b;2007a).

This combination of approaches is used in the update of ecological scarcity 2013 (Frischknecht & Büsser Knöpfel 2013).

3.3.6 Land use impacts on soil quality according to Milà i Canals

The method according to Milà i Canals et al. (2007c ;2007a) uses soil organic matter (SOM) as an indicator for soil quality. The deficit of SOM is calculated and used as characterisation factor.

Soil organic matter content does not fully consider all aspects of soil functions, but is qualified as a key soil quality indicator, especially for assessing the impacts on fertile land (agriculture and forestry systems). It influences properties like buffer capacity, soil structure and fertility.

The soil organic matter content can be measured directly from soil samples, calculated using local datasets and locally adjusted models, and estimated from literature values for different areas and crops. Characterisation factors for several land use types have been calculated using local datasets by Milà i Canals et al. (2007a).

3.4 Comparison of the characterisation factors

Fig. 3.3 shows characterisation factors of the different land use indicators normalised with the characterisation factor of "occupation, urban continuously built". The land use types are sorted in ascending order of the charactisation factors of de Baan & Olson.

The figure clearly shows the differences between the indicators based on biodiversity, biotic production potential and soil organic matter deficit compared to indicators based on land competition like Lugschitz. Indicators like Lugschitz simply add up the occu-

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6 Personal information, Laura de Baan, ETH Zurich, May 3rd, 2012

pied land without any further characterisation. Therefore, the impact of one square meter completely sealed urban area causes the same “impact” as one square meter of extensively managed forest.

Traffic related and industrial land use types show the most similar characterisation factors independent of the approach.

There are, however, some large discrepancies. The characterisation factors of de Baan & Olson and of Köllner differ substantially with regard to permanent crop and agricultural area. One important reason for this lies in the differences in species selected (animal and plants (de Baan & Olson) versus plants only) to quantify biodiversity. Especially the plant species richness in industrial areas or rail embankment is high due to low human interferences, while overall species richness is not. This is shown in the supportive material of de Baan et al. (2012).

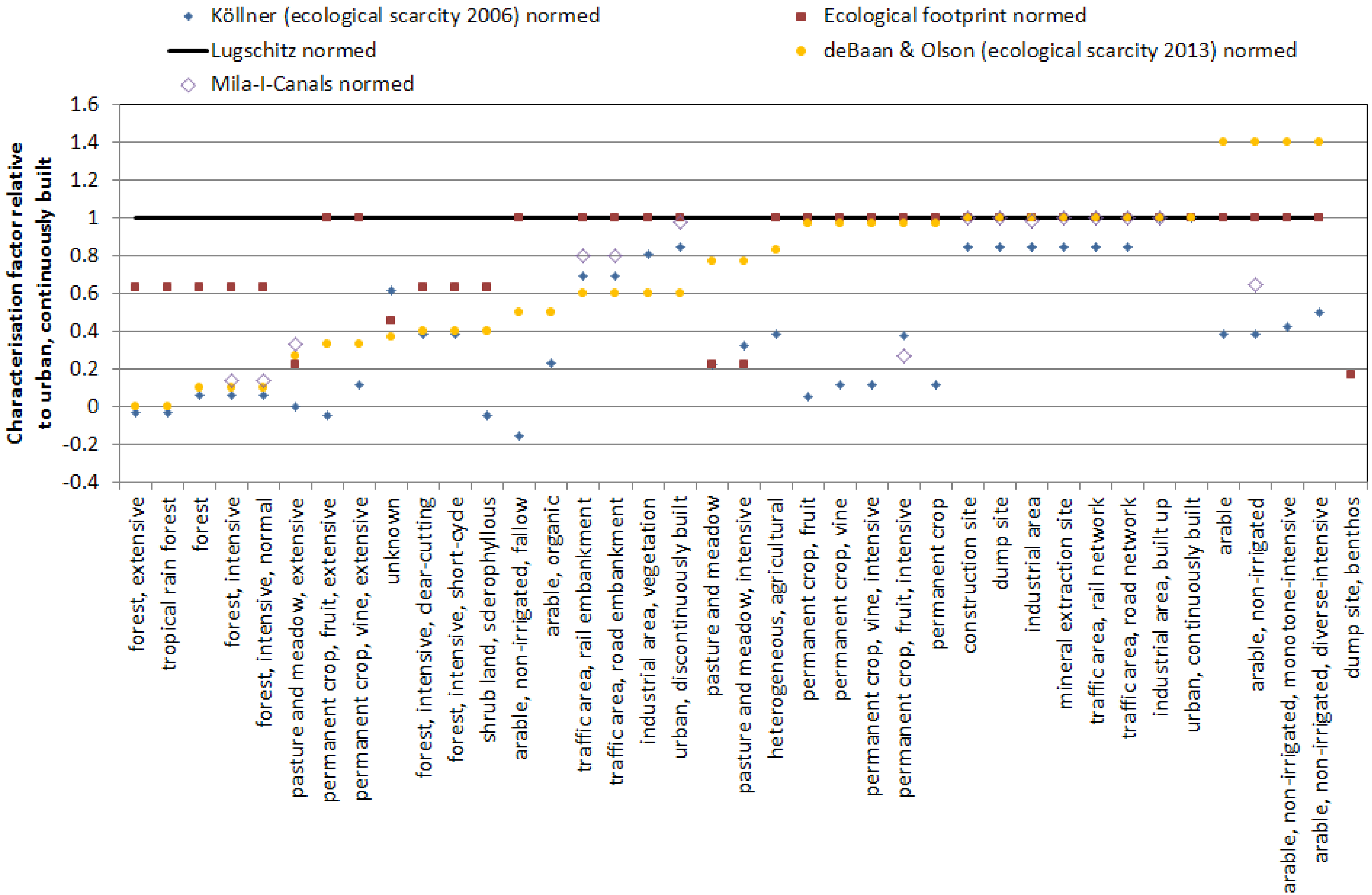

Fig. 3.3 Comparison of the characterisation factors of the different land use indicators normalised with the characterisation factor of "occupation, urban continuously built"

Tab. 3.3 shows the correlation coefficients of the characterisation factors of the different land use indicators analysed. In general the correlation of all indicators is medium to high except for Lugschitz. The calculation of a correlation coefficient for Lugschitz is not possible since there is no variation in the characterisation factors.

The correlation between Köllner and Milà i Canals is the highest. However this is considered to be an artefact because the two approaches cover completely different safeguard subjects and because Milà i Canals distinguishes a low number of different land use types.

Milà i Canals and ecological footprint show an elevated correlation because the indicators according to Milà i Canals and the ecological footprint represent damages on a similar ecosystem service.

Because there is no quantified overall environmental damage indicator available (like it is with regard to water use), the correlation analysis is only performed within the indicators analysed. It does not support a selection of an indicator with regard to the one representing overall environmental damages most appropriately.

Tab. 3.3 Correlation coefficient of the characterisation factors of the different land use indicators analysed correlation coefficients above or equal to 0.50 and above or equal to 0.90 are highlighted with light and dark grey colour, respectively; n.d.: not defined

Correlation coefficient	Lugschitz	Ecological footprint	Köllner	De Baan & Olson	Milà i Canals
Lugschitz	n.d.	n.d.	n.d.	n.d.	n.d.
Ecological footprint		1.00	0.39	0.55	0.69
Köllner			1.00	0.47	0.96
de Baan & Olson				1.00	0.66
Milà-i-Canals					1.00

3.5 Evaluation of the land use indicators

3.5.1 Overview

Tab. 3.4 shows the summary of the evaluation of the five indicators analysed according to Schwegler et al.'s (2011) scheme of "True & Fair View". A detailed evaluation is shown in Appendix B.

The main differences between the indicators analysed occur in the environmental relevance, communicability, data availability and complexity of the implementation.

Tab. 3.4 Comparison of the land use indicators according to the “True & Fair View” requirements; +: good performance; -: bad performance; +/-; both good and bad performance

Topic	Land use				
Indicator	Lugschitz	Ecological footprint	Köllner	de Baan & Olson	Milà i Canals
Environmental relevance	-	+	+	+	+
Focus on the overall picture	+/-	+/-	+/-	+	+/-
Reliability	+	+	+	+	+
Transparency	+	+	+/-	+/-	+
Comprehensibility / communi-cability	+/-	+/-	+/-	+/-	-
Coherence and Comparability	+	+/-	+/-	+/-	+/-
Availability of information: Data availability and quality	+	+/-	+	+	+
Timeliness (up-to-date infor-mation)	+	+	+	+	+
Ease of the implementation	+	+	+	+/-	+/-

3.5.2 Environmental relevance

None of the indicators analysed covers all environmental impact pathways and safe-guard subjects (biodiversity and ecosystem services). They rather focus on one particu-lar aspect.

The three ecosystem services indicators analysed (Lugschitz et al., Milà i Canals et al. and ecological footprint) cover land competition, soil organic carbon and biotic production potential, respectively whereas the two biodiversity indicators (Köllner and de Baan & Olson) cover relative species richness of plants and plants and animals, respectively. The indicator “land competition” of Lugschitz et al. (2011) hardly links to environmental impacts. The biodiversity indicators of Köllner and de Baan & Olson use a sample of about 5500 different plant species and about 1000 plant and animal species to quantify the relative species richness of different land use types.

Covering selected impact pathways, the final choice of a midpoint indicator involves value judgements (e.g., either biodiversity or ecosystem services).

3.5.3 Focus on the overall picture

Land use and its effects on the environment show three main characteristics. Firstly, land use causes a variety of different environmental impacts, either affecting ecosystem services for humans or affecting biodiversity. Secondly environmental impacts depend on the kind of land use, i.e. the purpose for which land is being used (managed forestry, agriculture, roads and settlements, mining sites, etc.). And thirdly, environmental impacts are highly dependent on the region, where the land is being used.

The approach of Lugschitz disregards purpose and regionalisation (location) by simply adding up square meters. The approach of the ecological footprint and Köllner disregard regionalisation using global average potential productivities (at least according to the publicly available data) and Swiss average biome, respectively, whereas the approaches of Milà i Canals and de Baan & Olson provide regionally differentiated characterisation factors.

The biodiversity indicator of de Baan & Olson quantifies biodiversity on the basis of global data and taking plant and animal species into account, whereas the indicator of Köllner uses Swiss data and quantify plant species richness only. Combined with information from Köllner, the indicator of de Baan & Olson is able to distinguish different types of agricultural practices (integrated, extensive and organic production).

The ecosystem service indicators ecological footprint and Milà i Canals distinguish several land use or soil types, which allows for an appropriate differentiation of their indicator. The biodiversity indicators according to de Baan & Olson and Köllner distinguish more than 57 different land use types.

Hence, Milà i Canals and de Baan & Olson as well as Köllner are the most sophisticated indicators in their respective category (ecosystem services and biodiversity). With regard to global coverage and biodiversity impacts, de Baan & Olson is more complete compared to Köllner.

3.5.4 Reliability

The indicators show substantially different levels of sophistication. They are all tailored to applicability in a life cycle thinking context and thus include simplifications and extrapolations. All the indicators analysed are scientifically sound and reliable.

3.5.5 Transparency

The calculations of all characterisation factors are published, transparent and can be reproduced. However, the modelling and calculations of the biodiversity based indicators (Köllner and de Baan & Olson) are more complex compared to the other indicators.

3.5.6 Comprehensibility (communicability)

Land use is commonly associated with square meters. The indicators of Lugschitz, ecological footprint, Köllner and de Baan & Olson quantify square meters and square meters equivalents[7]. While square meters equivalents are more demanding, a one to one addition of square meters will be questioned because differences in environmental impacts caused by different land use types are obviously neglected. The indicator Milà i Canals quantifies the amount of carbon deficit per hectare, which is less intuitive compared to square meters.

Hence, indicators using square meters and square meter equivalents are similarly understandable.

3.5.7 Coherence and comparability

The indicators analysed show a high level of coherence and comparability. It is highest for the indicator of Lugschitz because of its simple nature. All other indicators prove to be scalable and extendable, given that the necessary information is available. The biodiversity approach of de Baan & Olson is extended to cover land uses all over the world.

The ecosystem services indicators may be extended to cover more different soil and land use types. They are also suited to accommodate regionalised information and characterisation factors.

3.5.8 Availability of information (data availability and quality)

Data availability and quality covers the issues of land use types on one hand and regionalisation on the other. Due to data availability reasons the number of different land use or soil types considered in the indicators ecological footprint, and Milà i Canals is rather limited. The indicator according to Köllner differentiates several land use types but does not distinguish between different biomes. Within the indicator of de Baan & Olson data compatibility limitations are overcome by extrapolation using biome specific average plant biodiversity information.

Data availability and quality is hardly a problem for the indicator of Lugschitz, because of its simple characteristic. The indicator of Milà i Canals may rely on measured, modelled or estimated data (ISRIC-WISE soil database (Batjes 2005)) with data quality being higher for the former compared to the latter.

There is a clear trade-off between the requirement on data of a global coverage, regional differentiation and land use type differentiation on one hand and data availability on the other. Limitations in data availability call for extrapolations and estimations which has an influence on data quality. The loss in data quality is however considered to be of less importance compared to the global coverage and differentiation gained with extrapolations and estimations. With this premise the indicator of de Baan & Olson shows the best data availability to data quality ratio.

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7 In fact they quantify „square meters times years“ to reflect both the area and the occupation time.

3.5.9 Timeliness (up-to-date information)

Actuality is less important with regard to the three ecosystem service indicators Lugschitz, Milà i Canals and ecological footprint. The biodiversity indicators rely on information which is mostly less than ten years old. Hence, all indicators analysed are sufficiently up to date.

3.5.10 Ease of implementation

The impacts on biodiversity vary according to the region (or biome) the land is being used and according to the type of activity the land is being used for (agriculture, settlements, forestry). The implementation of land use indicators in LCA databases must consider the following two aspects. Firstly, some of the indicators evaluated require regionalised information on land use and secondly the indicators require a differentiation according to land use (or soil) types.

The indicators according to Lugschitz, Köllner and ecological footprint are already implemented in ecoinvent data v2.2. The implementation of the indicators of Baan & Olson (average) and Milà i Canals is straightforward because the characterisation factors are readily available or can easily be made available.

The implementation of regionally differentiated characterisation factors according to de Baan & Olson is rather difficult. The ecoinvent database does not yet provide the necessary regionally differentiated information. Thus the life cycle inventory datasets need to be adjusted. This can be done by distinguishing land use types according to the 14 biomes used in the approach of de Baan & Olson.

3.6 Further indicators, not analysed in detail

3.6.1 ReCiPe midpoint

ReCiPe midpoint uses the competition approach, i.e. all different types of land uses are added up (Goedkoop et al. 2009) without characterisation. The method is not analysed in detail because it is identical to the approach of Lugschitz (2011).

3.6.2 Baitz

The method proposed by Baitz (2002) and further developed by Bos and Wittstock (Bos & Wittstock 2007) is based on an inventory of seven indicators that can be used to describe the impacts related to land occupation and transformation. For each indicator, a description and a classification is given for its dependence on a set of fundamental quality parameters, such as the main soil types, the slope of the landscape, the carbon content and the maturity of the landscape. The following indicators are to be used:

- Erosion stability,
- Filter, buffer and transformation function for water,
- Groundwater availability and protection,

- Net Primary Production (NPP),
- Water permeability and absorption capacity,
- Emission filtering absorption and protection, and
- Ecosystem stability and biodiversity.

Until now, the different indicators cannot be combined or weighted at the midpoint level. All indicators are calculated as elementary flows that in a next step should be used as indicators to characterise impact categories which are yet to be defined.

The use of a set of several different indicators, which cannot be weighted or combined at a midpoint level is rather complicated. Regional and local information on the land and its soil quality would be required. Furthermore, the documentation of the indicator is not accessible. Therefore, this method is not analysed in detail.

3.6.3 HANPP

The human appropriation of net primary production (HANPP) is a productivity based indicator that reflects both the amount of area used by humans and the intensity of the land use. HANPP measures to what extent the land conversion and biomass harvest alter the productivity of ecosystems. It is a measure for the intensity of human activities compared to natural processes (Haberl et al. 2012).

The research questions behind HANPP are (Haberl et al. 2004): how intensively is a defined area of land being used in terms of ecosystem energetics? On a given territory, how much energy is diverted by humans as compared with the energy potentially available? How strongly does human use of a defined land area affect its primary productivity, and how much of the NPP is harvested by humans and, therefore, not available for non-human processes?

HANPP can be expressed as material flow (kg dry matter biomass), as a substance flow (kg carbon) or as an energy flow (Joule). Also, HANPP can be presented as a percentage of potential NPP. The assumption behind HANPP is that the flow of trophic energy described is a prerequisite for the functioning of ecosystems, and that reducing energy availability for ecosystem processes such as the build-up and maintenance of biomass stocks or for reducing the flow of energy from autotrophs to herbivores, detritivores and carnivores of different trophic levels affects ecosystems.

The assessment of HANPP based on LCA methods would be possible because the data are available in GIS on a grid scale of 0.5° x 0.5°. However, considerable conceptual challenges have to be overcome for this approach to become operational. In particular, the characterisation factors of different land use types in different countries have to be elaborated.

This indicator is not analysed in detail because of the methodological challenges in the implementation of this indicator in an LCA context.

3.6.4 Feldwisch et al. 2006

The tool developed by Feldwisch et al. (2006) aims to combine the main soil functions such as living environment, ecosystem, buffer, and archival functions in one statement. Therefore, the different soil functions are assessed separately and summarised to a usable statement considering the importance of a certain soil at a certain place. Depending on the scope of the assessment different methods are used to combine all relevant soil functions. The tool is mainly used as a foundation for land use planning on a local level (community or city).

The method is not analysed in detail because it does not provide any quantitative characterization factors for the individual soil functions. The unavoidable weighting of all soil functions to a single statement is similar to the LCA endpoint methods which are explicitly excluded from this study. The application on community level and thus, the efforts for the necessary adaptations to the inventory data is considered to be disproportionate to the insights gained.

3.6.5 Staub et al. 2011

Staub et al. (2011) developed a methodology for the operationalization of the ecosystem services through welfare-significant environmental indicators. The aim is to show the contribution of the ecosystem to welfare, whereby not only land use but also water and air quality issues are considered.

The method is not analysed in detail because it does not provide any characterization factors. Furthermore, land use and land use quality (biodiversity) are not characterised as one indicator but part of several individual indicators such as cultural services (recreational and aesthetic values) and regulating services (natural hazard protection, erosion protection). The method is far away from an operationalisation in an LCA context.

3.6.6 Frick 2012

Frick (2012) refers to an internal FOEN document. It shows the results of a census conducted in 2011. People were asked how they experience landscape in terms of structure, character, fascination, authenticity, beauty, quality and identification.

The method is not analysed in detail because the indicators of interest would be those which refer to soil quality. Especially with regard to the assessment of landscape quality, measurements of physical and chemical soil parameters are considered to be more appropriate compared to questionnaires completed by the local community.

3.6.7 Roth et al. 2010

Roth et al. (2010) give an overview of the state and development of the Swiss landscape based on the DSIPR model. Population density, living area, private transport, sealing, skilift, agriculture, etc. are considered.

The method is not analysed in detail because the indicators show their development in time and no characterization factors are given.

3.6.8 Impacts of land use according to Weidema & Lindeijer

Weidema & Lindeijer (2001) suggest different indicators to assess the impacts of land use, based on

- biogeochemical substance and energy cycles, being part of the impact chains for the life-support functions.
- actual or potential productivity of the ecosystems, relating to the availability of biotic resources, the potential for agriculture, and most of the life-support functions.
- biodiversity of the ecosystems, relating directly to the endpoint "Biodiversity" under "Resources", and also being indicators for species composition as a midpoint to other areas of protection.
- cultural value of the affected sites, in terms of uniqueness of landscapes and archaeological remains.
- migration and dispersal, as one of the midpoints towards altered species composition.

They propose the Net Primary Production (NPP) as a reasonable midpoint indicator for the impact on biotic resources, the potential for agriculture, and most of the life-support functions of natural systems.

For biodiversity, they develop an indicator that includes species richness, inherent ecosystem scarcity (expressed as the inverse of the potential ecosystem area that could be occupied by the ecosystem if left undisturbed by human activities), and ecosystem vulnerability (indicating the relative number of species affected by a change in the ecosystem area, as expressed by the species-area relationship).

No quantifiable indicators have been elaborated to assess the remaining impacts listed above. There are no current advancements of these indicators since 2001. Only examples of a limited number of characterisation factors have been calculated and since 2001 the method was not developed further. Therefore, this method is not analysed in detail.

3.7 Recommendation

Biodiversity loss is considered as one of the main environmental threats worldwide. The importance of protecting biodiversity leads to the Intergovernmental Platform on Biodiversity and Ecosystem Service, IPBES, founded in 2012.[8] We thus recommend the

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[8] http://www.ipbes.net, accessed on May 3, 2013.

use of the indicator of de Baan & Olson as implemented in the ecological scarcity method 2013. It quantifies the damages of land use on plant and animal biodiversity and allows for a biome specific assessment. The indicator of de Baan & Olson uses global information sources on species richness.

4 Air pollutants

4.1 Scope of the indicator

The indicator “air pollutants” should represent the impacts on human health caused by conventional air pollution, excluding human health damages due to climate change, ozone depletion and ionising radiation.

The indicator should reflect the most important impacts of a broad range of air pollutants including carcinogenic and non-carcinogenic substances, photochemical oxidants and primary and secondary particulate matter (PM).

4.2 Impact pathways of particulate matter (PM_{10})

A substantial fraction of inhaled particles is deposited in the airways or lungs, where it can cause health problems. Among others, secondary PM_{10} aerosols are formed from emissions of SO_2, NH_3 and NO_x. These primary emissions of SO_2, NH_3 and NO_x have an additional noxious impact on human health and the environment. This indicator considers particulate matter emitted by or formed from anthropogenic sources.

Rates of chronic and acute respiratory symptoms, as well as mortality rates are strongly correlated with ambient particulate matter concentrations. Emission of primary PM_{10} as well as SO_2 and NO_x leading to secondary PM are responsible for elevated ambient PM_{10} levels.

Fig. 4.1 shows the impact pathways of primary (on the left) and secondary PM (on the right) derived from Humbert (2009) and Hauschild et al. (2011).

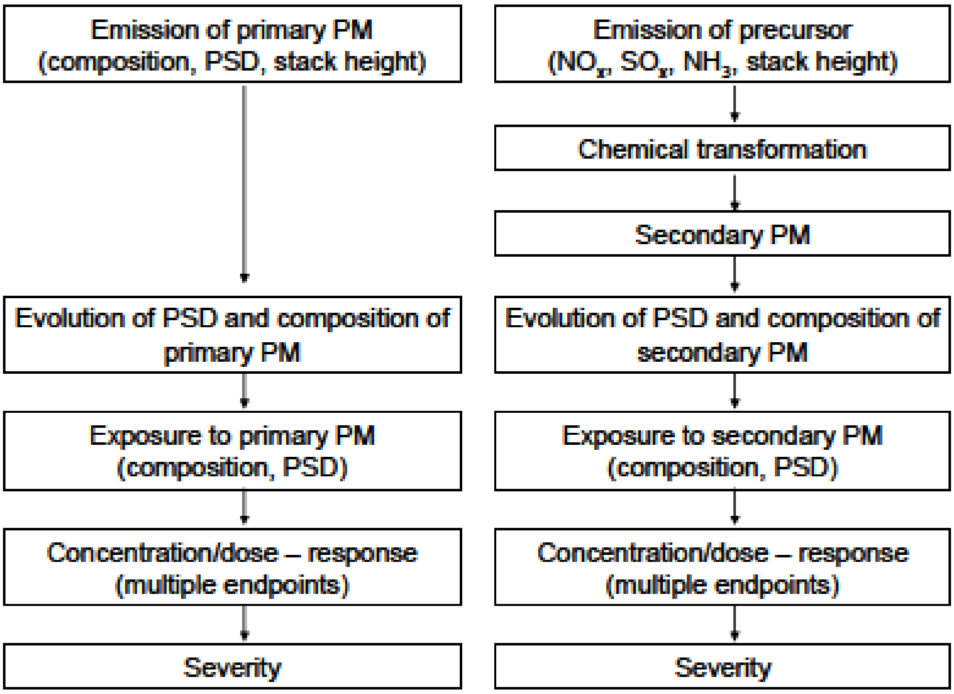

Fig. 4.1 Environmental mechanism for primary (left) and secondary particulate matter (right) derived from Humbert (2009) and Hauschild et al. (2011))
PSD: Particulate size distribution

4.3 Selection of the indicators

4.3.1 Overview

Six different indicators assessing impacts of air pollutants on human health are compared, namely the external damage costs (in Euro) according to NEEDS (New Energy Externality Development for Sustainability), disability adjusted life years (DALY)[9] according to eco-indicator 99, DALYs according to IMPACT2002+, DALYs according to ReCiPe endpoint and particulate matter emissions in tons of PM10-equivalents? according to ReCiPe midpoint and TRACI 2.1.

Only impacts of air emissions on human health are considered. Impacts on human health caused by the emissions of greenhouse gases, ozone depleting substances and ionising radiation are excluded from the total. The indicators analysed are independent of the geographic location of the emission although some of them would also allow for

9 The disability-adjusted life year (DALY) is a measure of overall disease burden, expressed as the number of years lost due to ill-health, disability or early death.

a regionalised assessment or an assessment which differentiates regions with low and high population densities.

Tab. 4.1 shows an overview of the different indicators analysed including a short description of the included material flows.

Tab. 4.1: Overview of the indicators assessing impacts of air pollutants analysed in detail

Name	Abbre-viation	Secon-dary parti-cles	Carcino-genic sub-stances (general)	Diesel soot	Excluded air emis-sions	Source
External costs ac-cording to NEEDS	NEEDS	Yes	No	No	Ionising radiation	NEEDS 2009
Environmental im-pacts of air pollutants in DALYs according to eco-indicator 99	Eco-indicator 99	Yes	Yes	Yes	Greenhouse gas emissions, ozone depleting substances and ionising radiation	Goedkoop & Spriensma 2000
Environmental im-pacts of air pollutants in DALYs according to IMPACT2002+	IMPACT 2002+	Yes	Yes	No	Ozone depleting substances and ionis-ing radiation	Margni et al. 2003
Environmental im-pacts of air pollutants in DALYs according to ReCiPe endpoint	ReCiPe endpoint	Yes	Yes	No	Greenhouse gas emissions, ozone depleting substances and ionising radiation	Goedkoop et al. 2009
Particulate matter emissions according to ReCiPe midpoint	ReCiPe midpoint	Yes	No	No	none	Goedkoop et al. 2009
Particulate matter emissions according to TRACI	TRACI	Yes	No	No	none	Bare 2011

A more detailed description of the individual indicators is given in the Sections 4.3.2 to 4.3.6.

4.3.2 External costs according to NEEDS

The quantification of external costs according to NEEDS is based on an 'impact path-way' methodology. The impact pathway analysis models the causal chain of interactions from the emission of a pollutant through transport and chemical conversion in the at-mosphere to the impacts on various receptors, such as human beings, crops, building materials or ecosystems. Welfare losses resulting from these impacts are transferred into monetary values based on the concepts of welfare economics (NEEDS 2009).

Damage to human health and external costs due to the emission of primary and secondary particulate matter, NMVOCs, heavy metal emissions (Cd, As, Ni, Pb, Hg and Cr), formaldehyde, dioxins and radionuclides are taken into account in the present analysis.

The NEEDS project calculated 'average' external costs for typical configurations. NEEDS thus uses unit damage costs that refer to the EU-27 average and to emissions occuring in the year 2010.

4.3.3 Eco-indicator 99

The method eco-indicator 99 (Goedkoop & Spriensma 2000) is a damage oriented approach and one of the parent methods of the ReCiPe method.

The air pollutants included which damage human health comprise carcinogenic substances, photochemical oxidants and primary and secondary particulate matter.[10]

Fate analysis, dose-response relations and damage analysis is based on Hofstetter (1998).

4.3.4 IMPACT 2002+

The life cycle impact assessment method IMPACT 2002+ is a damage oriented approach, which for several impact categories relies on the Eco-indicator 99 (Margni et al. 2003).

The air pollutants included which damage human health comprise carcinogenic and non-carcinogenic substances, photochemical oxidants and primary and secondary particulate matter.[11]

Fate analysis, dose-response relations and damage analysis is based on Hofstetter (1998).

4.3.5 ReCiPe midpoint and endpoint

The ReCiPe 2008 method (Goedkoop et al. 2009) is a damage oriented impact assessment method.

In this comparison the contribution of the air pollutants to the safeguard subject human health according to ReCiPe endpoint (hierarchist perspective) are analysed (excluding impacts on human health due to climate change, ozone depletion and ionising radiation).

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[10] As mentioned above, in this comparison the contribution of air pollutants to the safeguard subject human health are analysed excluding impacts on human health due to climate change, ozone depletion and ionising radiation.

[11] As mentioned above, in this comparison only the contribution of the air pollutants to the safeguard subject human health are analysed excluding ozone depletion and ionising radiation impacts.

The air pollutants included comprise human toxic substances (including carcinogenic substances), photochemical oxidants and primary and secondary particulate matter.

- The end point indicator used for the assessment of impacts of particulate matter on human health is based on Van Zelm (2008) and uses DALYs. The model EUTREND (Van Jaarsveld 1995) is as fate model and the model LOTOS-EUROS (Schaap et al. 2008) is used to model the intake fractions. The damage factors are based on Van Zelm (2008).
- The midpoint indicator particulate matter aggregates the amounts (mass) of primary particulate matter emitted and the amounts of secondary particulate matter formed by the emission of NO_X, SO_2, and NH_3. The reference substance is particulate matter (in tons) and the unit of the midpoint indicator is particulate matter equivalents.

4.3.6 TRACI

The fate and transport of these substances from the point of emission to human exposure differ depending on the source of the emissions. The original methodology utilised in TRACI 1.0 (Bare J. C. et al. 2003) has not been changed except that $PM_{2.5}$ is now used as a reference substance.

TRACI (Bare 2011) uses a damage oriented three-stage model to quantify the impacts of primary and secondary particulate matter emissions on human health, covering fate, exposure and damage modelling.

The fate and exposure modelling is based on the CALPUFF model (Wolff 2000) and the damage modelling is based on epidemiological studies of Nishioka et al. (2002)

The air pollutants and impacts covered by TRACI are primary and secondary particulate matter.

4.4 Comparison of the indicators

4.4.1 Overview

The comparison of the different indicators is based on three levels. Firstly, a contribution analysis of a set of selected materials is carried out. Secondly, the characterisation factors of the particulate matter emissions of the different LCIA methods are compared. Finally, a correlation analysis based on the results of the set of selected materials is carried out.

4.4.2 Indicator results

Fig. 4.2 shows the contribution of the most important air pollutants to the total human health damage caused by the supply of 1 kg of material. The relative contributions are based on the average of the contribution of the pollutants to the impacts on human health caused by a set of 52 selected materials. The list of selected materials is shown in Tab. 6.2 (Page 73).

The share of the impacts on human health caused by primary and secondary particulate matter emissions varies between 86 % (IMPACT2002+) and 96 % (Eco-indicator 99). The remaining air pollutants like human toxic substances (heavy metals, dioxins), carcinogenic and non-carcinogenic substances and photochemical oxidants) only have an average contribution of between 4 and 14 % to the total impacts on human health.

The contribution of secondary particulate matter (sulphur dioxide, nitrogen oxides and ammonia) and primary particulate matter (PM_{10} and $PM_{2.5}$) are very similar across all indicators except TRACI, where nitrogen oxides have a lower and $PM_{2.5}$ emissions have a higher contribution compared to all the other indicators. Impact 2002+ is the only indicator which excludes particulate matter with a size bigger than 2.5 μm.

VOC emissions contribute only little to the health costs of air pollution in Switzerland although the amounts emitted annually are the largest among the pollutants listed above. The share on human health related external costs caused by the annual emissions of VOC in Switzerland on the total human health related external costs caused by the emissions of particulate matter, VOC, SO_2, NH_3 and NO_X is about 7 %. This finding is supported by Ecoplan (2012). They assessed the external costs of the various scenarios within the energy strategy 2050 of the Federal Council (Schweizerischer Bundesrat 2011) taking into account primary and secondary particulate matter but not VOC nor other air pollutants.

Based on this analysis it is concluded that indicators, which comprise primary and secondary particulate matter formation sufficiently represent human health damages caused by air pollution. Such an indicator covers PM2.5, PM10, NO_X, SO_2 and NH_3.

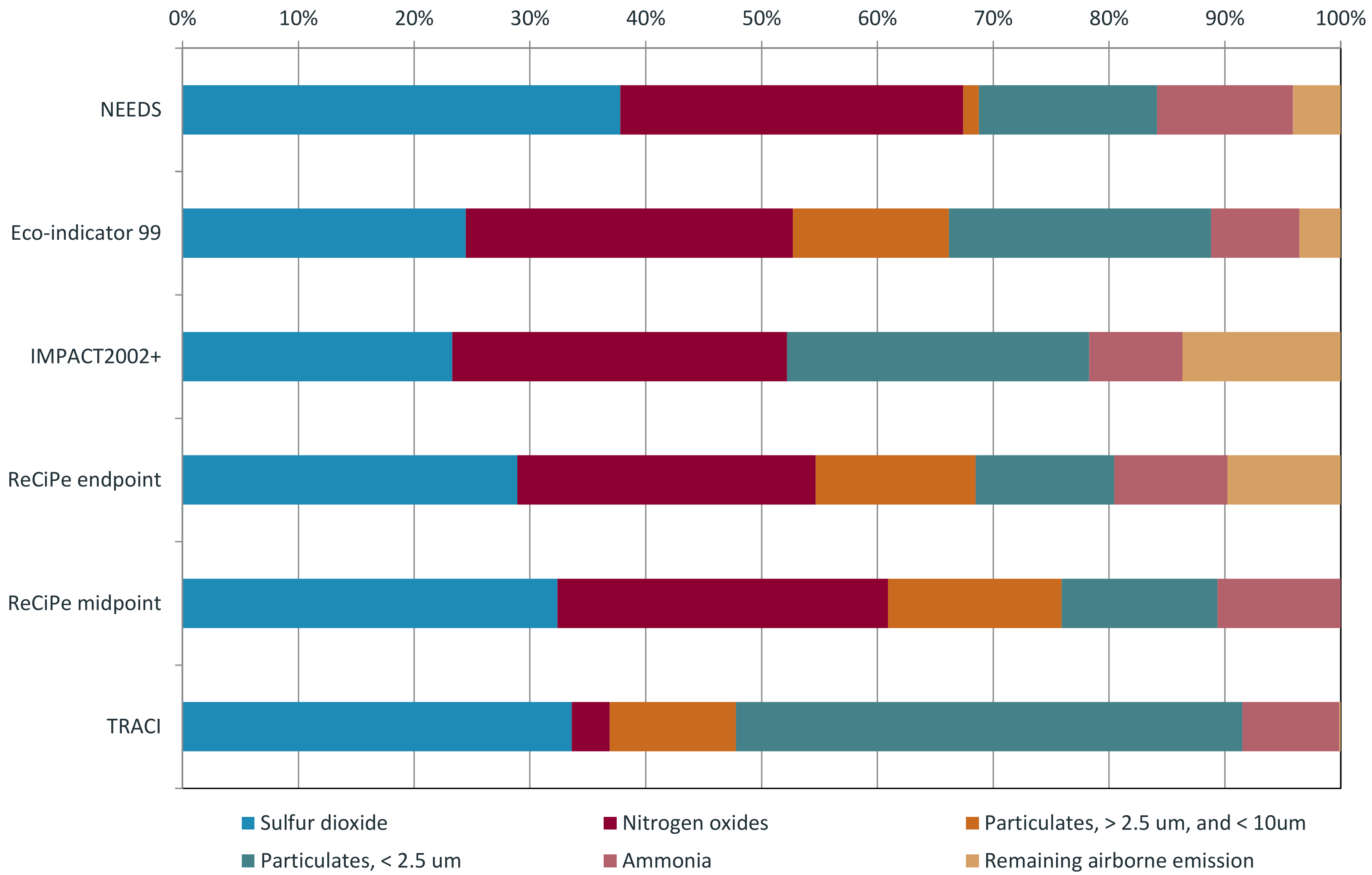


Fig. 4.2 Contribution of the different air pollutants to the total impacts of all air pollutants (including VOCs) on human health, excluding greenhouse gases, ozone depleting substances and ionising radiation; ReCiPe midpoint and TRACI only cover primary and secondary particulate matter.

4.4.3 Characterisation factors

Fig. 4.3 shows the comparison of the characterisation factors of the indicators analysed for primary and secondary particulate matter emissions relative to the characterisation factor of ammonia. Except in case of $PM_{2.5}$ there are no major differences in the characterisation factors across all indicators analysed.

IMPACT2002+ and Eco-indicator 99 use the same characterisation factors for primary particulate matter emissions. The same is true for ReCiPe midpoint and ReCiPe endpoint. The methods mentioned also apply the same characterisation factors for pollutants leading to secondary particulates (SO_2, NO_X, NH_3).

In the case of $PM_{2.5}$ the characterisation factor of TRACI is considerably higher than those of all other indicators and there is a considerable difference between ReCiPe and NEEDS on one hand and IMPACT2002+ and Eco-indicator 99 on the other.

The impacts of diesel soot on human health are explicitly characterised by Eco-indicator 99 only. Its characterisation factor is identical to the characterisation factor of particulate matter below 2.5 μm.

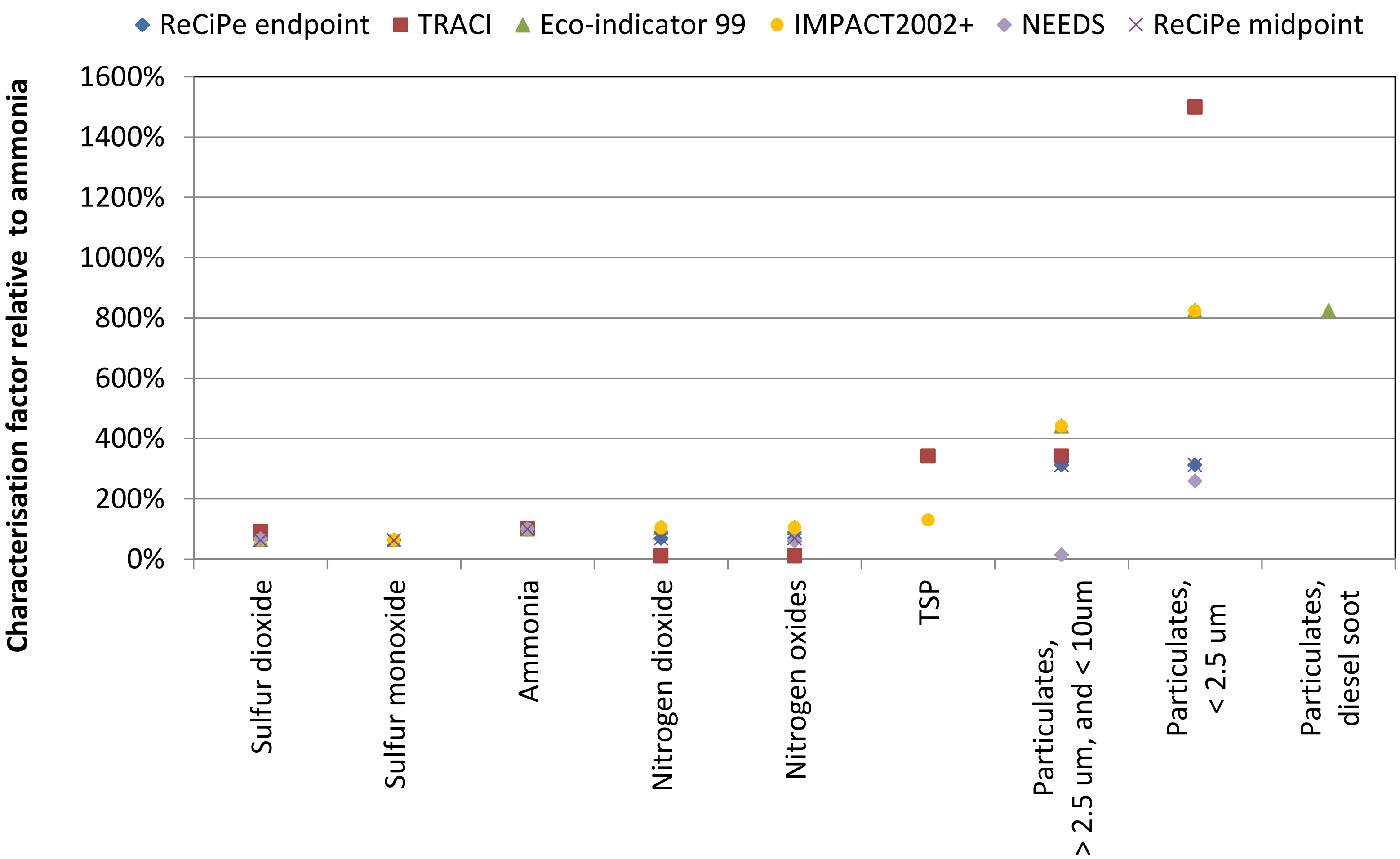


Fig. 4.3 Comparison of the characterisation factors for primary particulate matter and pollutants leading to secondary particulates according to the different indicators analysed relative to the characterisation factor of ammonia

4.4.4 Correlation analysis

Tab. 4.2 shows the correlation coefficients of the different air pollutant indicators and the midpoint indicators for particulate matter emissions (ReCiPe midpoint and TRACI) applied on the consumption of 1 kg of the selected materials shown in Fig. 6.3. The correlation of the different indicators is very high. All indicators show a very good correlation coefficient of 0.9991 or higher. Thus the exclusion of pollutants other than particulate matter and precursors of secondary particulate matter leads to very similar results.

Tab. 4.2 Correlation coefficient of the indicators analysed for 52 selected materials; correlation coefficients above or equal to 0.90 are highlighted with dark grey colour

Correlation coefficient	NEEDS	Eco-indicator 99	IMPACT2002+	ReCiPe endpoint	ReCiPe midpoint	TRACI
NEEDS	1.0000	0.9991	0.9998	0.9997	0.9997	0.9997
Eco-indicator 99		1.0000	0.9996	0.9998	0.9998	0.9997
IMPACT2002+			1.0000	0.9998	0.9998	0.9997
ReCiPe endpoint				1.0000	1.0000	1.0000
ReCiPe midpoint					1.0000	1.0000
TRACI						1.0000

4.5 Evaluation of the air pollutant indicators

4.5.1 Overview

Tab. 4.3 shows the summary of the evaluation of the six air pollutant indicators analysed according to the scheme of the "True & Fair View" study (Schwegler et al. 2011). A detailed evaluation is shown in Appendix C.

The indicators perform rather similar. The main differences between the indicators analysed occur in the transparency and timeliness.

Tab. 4.3 Comparison of the indicators representing air pollution according to the "True & Fair View" requirements;
+: good performance; -: bad performance; +/-; both good and bad performance

Topic	Air pollutants					
Indicators	NEEDS	Eco-indicator 99	IMPACT 2002+	ReCiPe endpoint	ReCiPe midpoint	TRACI
Environmental relevance	+	+	+	+	+	+
Focus on the overall picture	+	+	+	+	+	+
Reliability	+	+	+	+	+	+
Transparency	+/-	+/-	+/-	+/-	+	+
Comprehensibility / communicability	+/-	+/-	+/-	+/-	+/-	+/-
Coherence + Comparability	+/-	+/-	+/-	+/-	+/-	+/-
Availability of information: Data availability and quality	+	+	+	+	+	+
Timeliness (up-to-date information)	+	-	+	+	+	+
Ease of the implementation	+	+	+	+	+	+

4.5.2 Environmental relevance

The environmental relevance of the indicators Ecoindicator 99, IMPACT 2002+ and ReCiPe endpoint is the highest since these indicators consider more pollutants than just primary and secondary particulate matter, namely carcinogens, human toxic substances or photochemical oxidants. The indicator NEEDS considers selected human toxic substances but carcinogens or photochemical oxidants are missing. The two midpoint indicators ReCiPe midpoint and TRACI have the lowest environmental relevance since they only consider primary and secondary particulate matter. Given the fact, that the correlation among all indicators analysed is very high and that on average primary and secondary particulate matter cover more than 85 % of total human health damages caused by air pollution, this difference in environmental relevance is negligible. None of the indicators quantifies the number of particulates, which is considered to be more relevant compared to the total mass.

4.5.3 Focus on the overall picture

When looking at the overall picture all indicators are able to cover the most important air pollutants, namely primary and secondary particles. There is no major difference in the result between using more comprehensive endpoint indicators like Eco-indicator 99, IMPACT 2002+ and ReCiPe endpoint and less comprehensive midpoint indicators like ReCiPe midpoint and TRACI, which are able to cover the most important air pollutants as well.

4.5.4 Reliability

The indicators show substantially different levels of sophistication (from particulate matter formation models to complete fate, exposure and damage models). They are all tailored to applicability in a life cycle thinking context and thus include simplifications and extrapolations. All the indicators analysed are scientifically sound and reliable.

4.5.5 Transparency

The calculations of all characterisation factors are published, transparent and can be reproduced. However, the modelling and calculations of the endpoint indicators (Eco-ndicator 99, IMPACT 2002+ and ReCiPe endpoint) are more complex compared to the other indicators.

4.5.6 Comprehensibility (communicability)

The communicability of the external costs according to NEEDS is best, since monetary damage values are very easy to understand. However, within the framework of reporting the environmental impacts of Swiss consumption the unit would need to be transferred to a physical unit such as PM_{10}-equivalents. A similar conversion would be needed for indicators reporting in DALYs. Hence, all indicators show a similar easiness of understanding using particulate matter equivalents as a measure of impacts of air pollution on human health.

4.5.7 Coherence and comparability

Comparability of the times series of all indicators is given, as long as there are no changes in the impact factors.

4.5.8 Availability of information (data availability and quality)

The indicators analysed rely on complex models (Wolff 2000; Nishioka et al. 2002; Hofstetter 1998; Schaap et al. 2008; Van Jaarsveld 1995; Van Zelm et al. 2008). We propose to use the indicators as developed by scientists. Thus access to data, information and model parameters used to develop the characterisation factors is not required.

The emission data about main air pollutants are readily available in LCA databases such as ecoinvent data v2.2. The emissions of these pollutants within Switzerland are published annually.

4.5.9 Timeliness (up-to-date information)

All methods except the Eco-indicator 99 are up-to-date and have been updated in the recent past.

4.5.10 Ease of the implementation

All indicators analysed are already implemented in current LCA software and are easily applied.

4.6 Recommendation

We recommend the use of the ReCiPe midpoint indicator representing the mass of emissions of substances forming primary and secondary particulate matter. The indicator includes PM (different sizes), NO_X, SO_2 and NH_3. The ReCiPe midpoint is a comparatively simple midpoint indicator covering the most important air pollutants (primary and secondary particulate matter). The ReCiPe midpoint is scientifically sound and easily applied using current LCA software. The external costs according to NEEDS would be a more complex alternative to the ReCiPe midpoint including additional human toxic substances. However, the monetary units of the factors would need to be converted to a physical unit such as kg PM_{10}-equivalents.

5 Nitrogen / Eutrophication

5.1 Scope of the indicator

The indicator "nitrogen" is supposed to represent the environmental impacts of anthropogenic interference with the nitrogen cycle, which is predominantly eutrophication. According to Rockström et al (2009b) the broad use of nitrogen is one of the environmental aspects where mankind has clearly transgressed the respective planetary boundary. Together with changes in the use of Phosphorus, it is causing widespread eutrophication. This may end up causing long-term and profound changes in terrestrial, aquatic and marine systems. Because of the tight link between nitrogen and marine eutrophication, the correlation between nitrogen fixation and the eutrophying effect on marine ecosystems is analysed. Because freshwater eutrophication is mainly caused by phosphorous input, the correlation between the extraction of phosphorous resources and eutrophying effects in freshwaters is analysed too.

A large fraction of industrially fixed Nitrogen and industrially extracted Phosphorous is used in mineral fertilisers and thus ends up on the agricultural soil, in plants and partly also in water bodies.

In this chapter it is shown that the resource related indicators (industrial nitrogen fixation and phosphorous extraction) are not sufficiently valid proxies for eutrophying effects on marine and freshwater bodies, respectively. Because of insufficient correlations between nitrogen fixation and eutrophying effects in the environment, the most reliable emission based eutrophication indicator is recommended instead.

5.2 Selection of the indicators

5.2.1 Overview

Two different impact pathways for eutrophication are analysed, namely freshwater and marine eutrophication. The correlation of phosphorus extraction and freshwater eutrophication and the correlation of nitrogen fixation and marine eutrophication are analysed. The midpoints freshwater eutrophication and marine eutrophication according to ReCiPe (Goedkoop et al. 2009) are used as reference indicators in the correlation analysis. These indicators are recommended by the DG-JRC (Hauschild et al. 2011) and used, among others, in the product environmental footprint guide of the European Commission (European Commission 2012).

Tab. 5.1 shows an overview of the different eutrophication indicators analysed including the reference used in the correlation analysis.

Tab. 5.1: Overview of the different eutrophication indicators including the reference used in the correlation analysis

Name	Abbreviation	Reference for correlation analysis	Source
Marine eutrophication according to ReCiPe midpoint	Marine eutrophication	None	Goedkoop et al. 2009
Industrial nitrogen fixation	Nitrogen fixation	Marine eutrophication (sea and ocean)	ecoinvent Centre 2010
Phosphorus extraction from natural resources	Phosphorus extraction	Freshwater eutrophication (rivers and lakes)	ecoinvent Centre 2010

5.2.2 Marine eutrophication

Marine eutrophication is quantified using the CARMEN model implemented in the ReCiPe 2008 impact assessment method (Goedkoop et al. 2009). It quantifies the amounts of nitrogen emitted into the air, water and soil, ending up in marine environments. There is no regional differentiation with regard to the eutrophying impacts of the emissions of nitrogen compounds.

5.2.3 Nitrogen fixation

The indicator “nitrogen fixation” is derived from the life cycle inventory. The manufacturing processes of Ammonia (Haber Bosch), modelled in ecoinvent data v2.2

(ecoinvent Centre 2010), use atmospheric nitrogen as their main input. The total amount of industrial ammonia required in the life cycle of the different materials analysed is used to calculate the total amount of industrially fixed atmospheric nitrogen.

5.2.4 Phosphorus extraction

The indicator "phosphorus extraction" is derived from the life cycle inventory. The extraction of phosphorus resources is reported in ecoinvent data v2.2 (ecoinvent Centre 2010). The indicator "phosphorus extraction" corresponds to the sum of all the phosphorus extraction in the whole life cycle of the different materials analysed.

5.3 Correlation analysis

5.3.1 Overview

The correlation of nitrogen fixation and marine eutrophication and the correlation of the extraction of phosphorous resources and freshwater eutrophication are analysed. The correlation analysis is based on life cycle inventories of two different sets of materials. The first set includes a broad range of 58 materials, including mineral resources, biomass, meat, energy carriers, plastics, chemicals and metals and the second set only includes 18 materials of the two groups biomass and meat. This subset of the material selection is referred to as agricultural products. The selection of materials is shown in Tab. 6.2. Compared to the selection of materials in Chapter 6, the group of agricultural products has been extended because of the importance of the agricultural sector with regard to fertiliser consumption and eutrophying emissions to surface and groundwater.

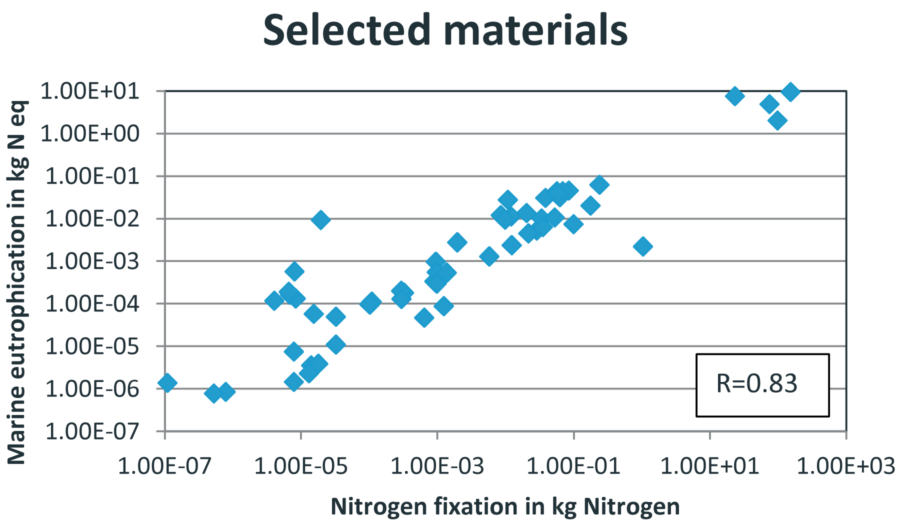
5.3.2 Nitrogen fixation and marine eutrophication

Fig. 5.1 shows the correlation of industrial nitrogen fixation and marine eutrophication based on a broad set of materials and the subset of agricultural products. It shows the life cycle based eutrophying impacts of a product on the y-axis and the corresponding amount of Nitrogen fixed on the x-axis. All data are extracted from ecoinvent data v2.2 and the treeze database.

The correlation between nitrogen fixation and marine eutrophication is rather high (correlation coefficient R of 0.83) in case of the broad set of selected materials.

The correlation between nitrogen fixation and marine eutrophication is very low for ammonium nitrate. This is expected because the life cycle inventory dataset of the production of artificial fertilisers considers the fixation of nitrogen but excludes the application of the fertiliser on the field. The application of the fertiliser is included in the life cycle inventory datasets of agricultural production (e.g. cultivation of tomatoes). The production of nylon, on the other hand, causes high eutrophying emissions with only low fixation of nitrogen.

The correlation is rather low in the case of agricultural products with a correlation coefficient R of 0.53. This deserves a closer look.



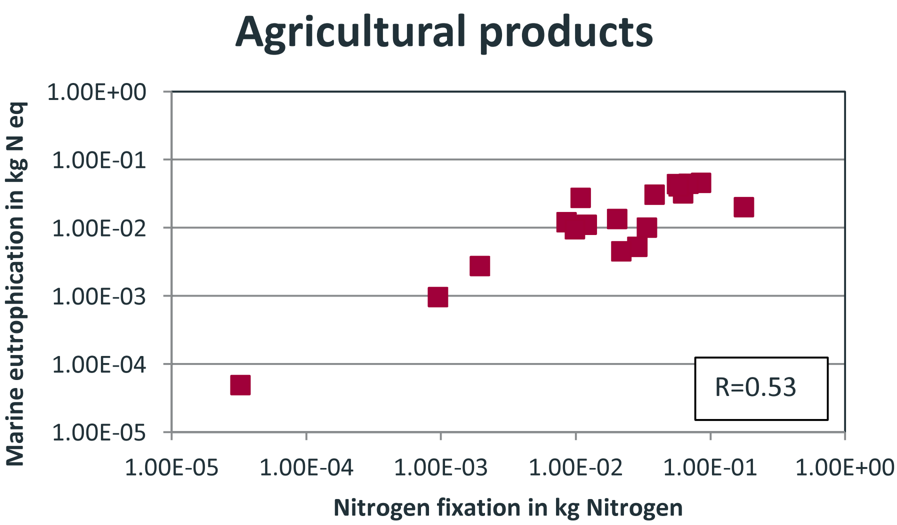


Fig. 5.1 Correlation plot and correlation coefficient of the fixation of nitrogen and marine eutrophication according to ReCiPe 2008 for selected materials and agricultural products

The input of nitrogen to agricultural land due to mineral fertilisers in Switzerland amounts to 52'000 tons compared to 86'300 tons of nitrogen due to manure (BAFU 2010). Further major inputs are the natural nitrogen fixation by plants (32'000 tons) and the deposition of nitrogen on agricultural land (27'000 tons). The correlation in case of agricultural products is thus influenced by the natural fixation of nitrogen and the eutrophying emissions due to the use of manure as an organic fertiliser which both do not add to the industrial fixation of nitrogen.

The nitrogen, which is fixed by plants or deposited on agricultural land, is mobilised by livestock breeding. The nitrogen fixed enters the system of livestock breeding as fodder plant and leaves the system as manure or slurry, which leads to eutrophying emissions without industrial fixation of nitrogen.

Furthermore, the eutrophying emissions, especially nitrate leaching to ground and surface water, strongly depend on the type of agricultural plant. The SALCA nitrate model (Richner et al. 2006) is used to quantify the nitrate leaching of the agricultural production processes represented in the ecoinvent datasets. The SALCA model uses different risk factors for nitrate leaching depending on the crop and on the month of the year.

Fig. 5.2 shows the correlation plot of nitrate leaching into ground and surface water in kg N and the total nitrogen input due to artificial fertilisers in kg N (top), liquid manure in m^3 per kg crop (middle) and solid manure in kg per kg crop (bottom) for selected agricultural plant products. Neither the artificial fertiliser input nor the liquid or solid manure input correlate with the leaching of nitrate into surface and ground water.

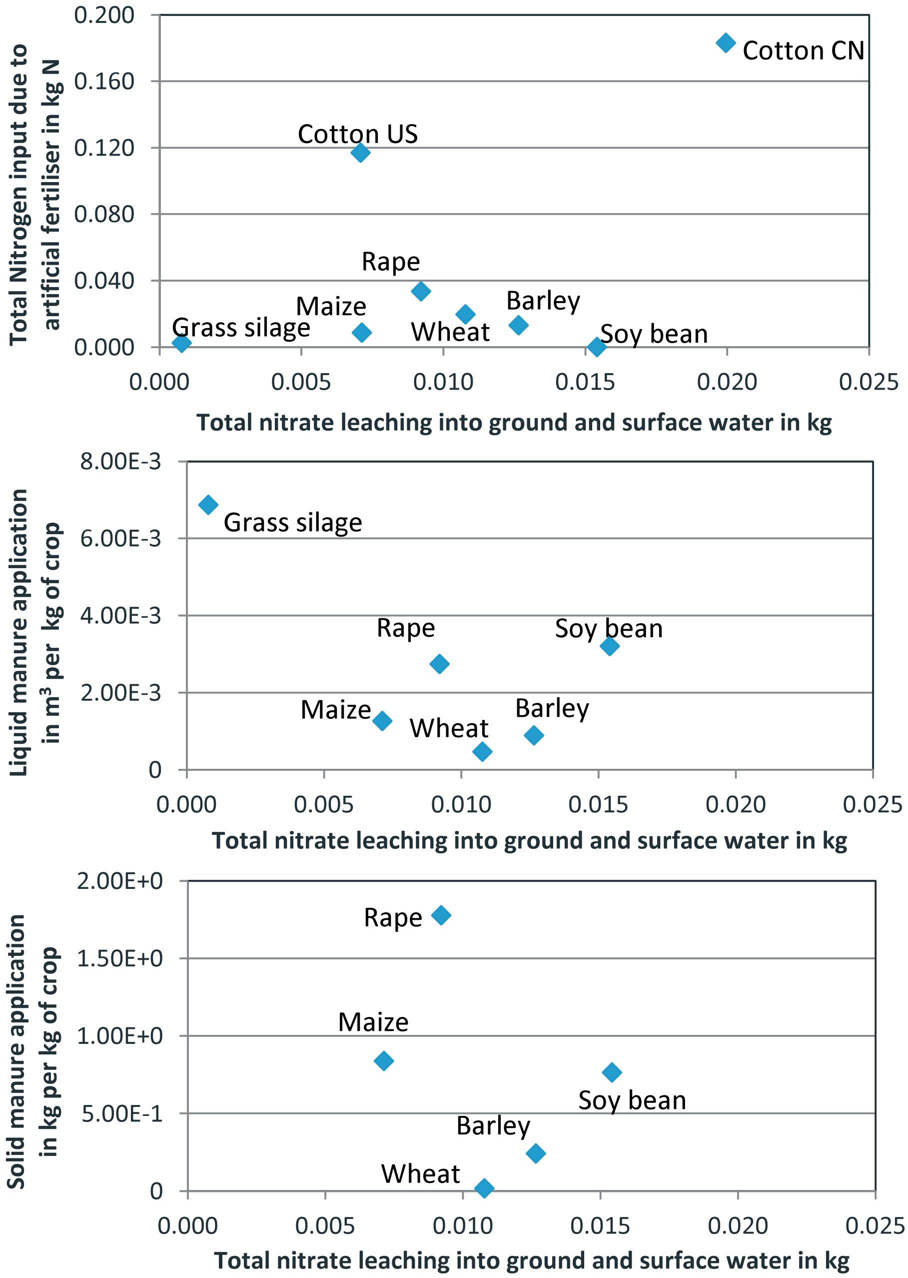


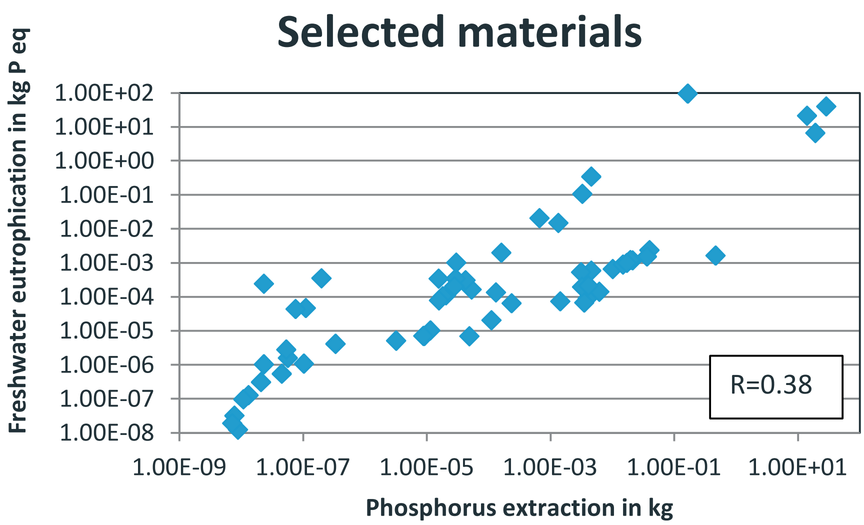
Fig. 5.2 Correlation plot of nitrate leaching into ground and surface water in kg N and the total nitrogen input due to artificial fertilisers in kg N (top), liquid manure in m^3 per kg crop (middle) and solid manure in kg per kg crop (bottom) for selected agricultural plant products

5.3.3 Phosphorus extraction and freshwater eutrophication

Fig. 5.3 shows the correlation of phosphorus extraction and freshwater eutrophication based on broad set of selected materials and the subset of agricultural products. In case of the agricultural products the correlation between the phosphorus extraction and the freshwater eutrophication is very high (correlation coefficient R of 0.96). The correlation for the broader set of materials is much lower (correlation coefficient R of 0.38).

The materials gold and triple superphosphate show a very low correlation with the phosphorus extraction. The extraction of gold emits high amounts of phosphate, which stems from sulphidic tailings, but at the same time requires only little amounts of phosphorus resources.

The production of triple superphosphate extracts a high amount of phosphorus resources but causes only little freshwater eutrophication. This is reasonable because the eutrophying emissions will only occur with the application of the fertiliser in the field.



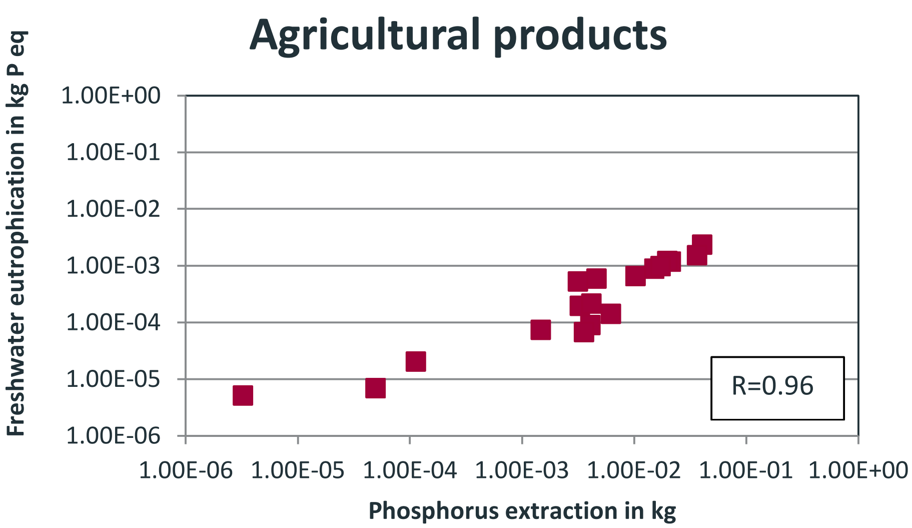


Fig. 5.3 Correlation plot and correlation coefficient of the extraction of phosphorus resources and freshwater eutrophication according to ReCiPe 2008 for selected materials (above) and agricultural products (below)

5.4 Evaluation of the nitrogen indicators

5.4.1 Overview

Tab. 5.2 shows the summary of the evaluation of the two eutrophication indicators analysed according to the scheme of "True & Fair View" in Schwegler et al. (2011) . A detailed evaluation is shown in Appendix D.

The main differences between the indicators analysed occur in the general view.

Tab. 5.2 Comparison of the indicators Nitrogen fixation and Phosphorus extraction according to the "True & Fair View" requirements;
+: good performance; -: bad performance; +/-; both good and bad performance

Topic	Nitrogen / Eutrophication		
Indicators	Nitrogen fixation	Phosphorus extraction	Marine eutrophication
Environmental relevance	+/-	+/-	+
Focus on the overall picture	+/-	+/-	+
Reliability	+/-	+/-	+
Transparency	+	+	+
Comprehensibility / communicability	+	+	+/-
Coherence and Comparability	+	+	+/-
Availability of information: data availability and quality	+	+	+
Timeliness (up-to-date information)	+	+	+
Ease of the implementation	+	+	+

5.4.2 Environmental relevance

Nitrogen fixation is not a sufficiently valid proxy for marine eutrophication even for the subset of agricultural products. The widespread use of manure (organic fertilisers) for instance in Switzerland and its eutrophying impacts are not appropriately represented by the Nitrogen fixation indicator.

In the case of agricultural products the phosphorus extraction is a valid proxy indicator for freshwater eutrophication. However, this is not true for a broader selection of materials.

The emission based marine eutrophication indicator according to ReCiPe midpoint has a significantly higher environmental relevance.

5.4.3 Focus on the overall picture

According to the current state of the environment in Switzerland and the North Sea, nitrogen emissions are still far too high compared to the critical loads agreed within the OSPAR agreement (OSPAR Commission 2008). That is why the indicator representing marine eutrophication is better suited to represent the overall picture as compared to the resource extraction indicators nitrogen fixation and phosphorous extraction.

5.4.4 Reliability

The nitrogen fixation and phosphor extraction data derived from the ecoinvent data v2.2 are considered reliable. The marine eutrophication is implemented in the ReCiPe 2008 impact assessment method (Goedkoop et al. 2009) and is considered as scientific sound and reliable.

5.4.5 Transparency

The indicators are directly derivable from or implemented in existing LCA databases such as the ecoinvent database. The ecoinvent data v2.2 are published, reliable and transparent.

5.4.6 Comprehensibility (communicability)

The nitrogen fixation and the phosphorus extraction indicators are rather easy to communicate. They are described by one number and a common physical unit (mass, kg). The marine eutrophication indicator is measured in Nitrogen-equivalents, which is considered to be more difficult to understand or interpret. The conversion of the equivalents is based on physical properties.

5.4.7 Coherence and comparability

The comparability of the time series is given for the nitrogen fixation and the phosphorus extraction indicators since both indicators describe a physical unit. In case the ecoinvent datasets on ammonia and phosphorus production are updated, time series would need to be recalculated. The comparability of the time series of marine eutrophication according to ReCiPe 2008 is given as well. If the characterisation factors for marine eutrophication are updated, the time series need to be recalculated as well.

5.4.8 Availability of information (data availability and quality)

The ecoinvent data 2.2 used for the calculation are available (yearly fee). The ReCiPe 2008 indicators are implemented in ecoinvent data v2.2.

5.4.9 Timeliness (up-to-date information)

The datasets on ammonia manufacture and phosphorus extraction reflect the situation in the years from 1995 to 2000 in case of ammonia production and from 1994 to 2001 in case of phosphorus extraction. Thus they are considered fairly up-to-date. The marine eutrophication according to ReCiPe 2008 was published in 2009 and is considered up-to-date as well.

5.4.10 Ease of the implementation

The implementation of these indicators is straightforward.

5.5 Recommendation

We recommend to focus on nitrogen and marine eutrophication and to use the indicator "marine eutrophication" according to ReCiPe as it is a widely used and solid indicator.

6 Environmentally relevant materials

6.1 Scope of the indicator

The indicator should reflect the consumption of materials in Switzerland and its environmental consequences. The indicator should focus on the environmental relevance (regarding potential impacts) but not on the resource aspect (scarcity, reserve to production ratio, dispersive use) of material consumption. The indicator should furthermore be usable in national statistics and be comparable with similar indicators used in the statistics of other OECD countries. Thereby it should offer a suitable alternative to the currently widespread use of domestic material consumption (DMC) as a main indicator for resource use, which does not take into account environmental impacts abroad anyhow.

6.2 Selection of the indicators

6.2.1 Overview

Four different material use indicators are compared, namely the domestic material consumption (DMC), the domestic raw material consumption (RMC), the total material consumption (TMC) and the environmentally weighted material consumption (EMC).

According to the mandate, the focus should be on physical indicators. However, because we identified a substantial trade-off between the criterion of environmental relevance and the avoidance of weighting, we also included a weighted indicator in the analysis (EMC).

The consumption perspective is chosen for the comparison of the indicators. The corresponding indicators based on the production perspective (domestic material input (DMI), domestic raw material equivalents (RME), total material requirement (TMR) and environmentally weighted material requirement (EMR)) are not analysed.

Tab. 6.1 shows an overview of the different indicators analysed including a short description of the included material flows.

Tab. 6.1: Overview of the material use indicators analysed in detail

Name	Abbreviation		Included material flows and emissions	Source
	Consumption perspective	Production perspective		
Domestic material consumption	DMC	DMI	Only direct material flows	BFS 2011
Domestic raw material consumption	RMC	RME	Direct and indirect flows excluding unused extraction	Schoer et al. 2012b
Total material consumption	TMC	TMR	Direct and indirect flows including unused extraction	Schütz & Bringezu 2008, BFS 2011
Environmentally weighted material consumption	EMC	EMR	Direct and indirect flows and emissions	van der Voet et al. 2009

Fig. 6.1 shows how the four indicators DMC, RMC, TMC and EMC are calculated. All four indicators consider domestic extraction, imports and exports resulting in a material consumption. The scope of the indicators increases from DMC, to RMC, TMC and finally EMC in that indirect flows (RMC), unused extraction (TMC) and emissions (EMC) are added to the domestic material consumption (DMC) indicator. Three of them (DMC, RMC and TMC) are based on an aggregation of physical (mass) flows, whereas the environmentally weighted material consumption (EMC) includes emissions to air, water and soil and applies an environmental impact assessment method. A more detailed description of the individual indicators is given in the Sections 6.2.2, 6.2.3, 6.2.4 and 6.2.5.

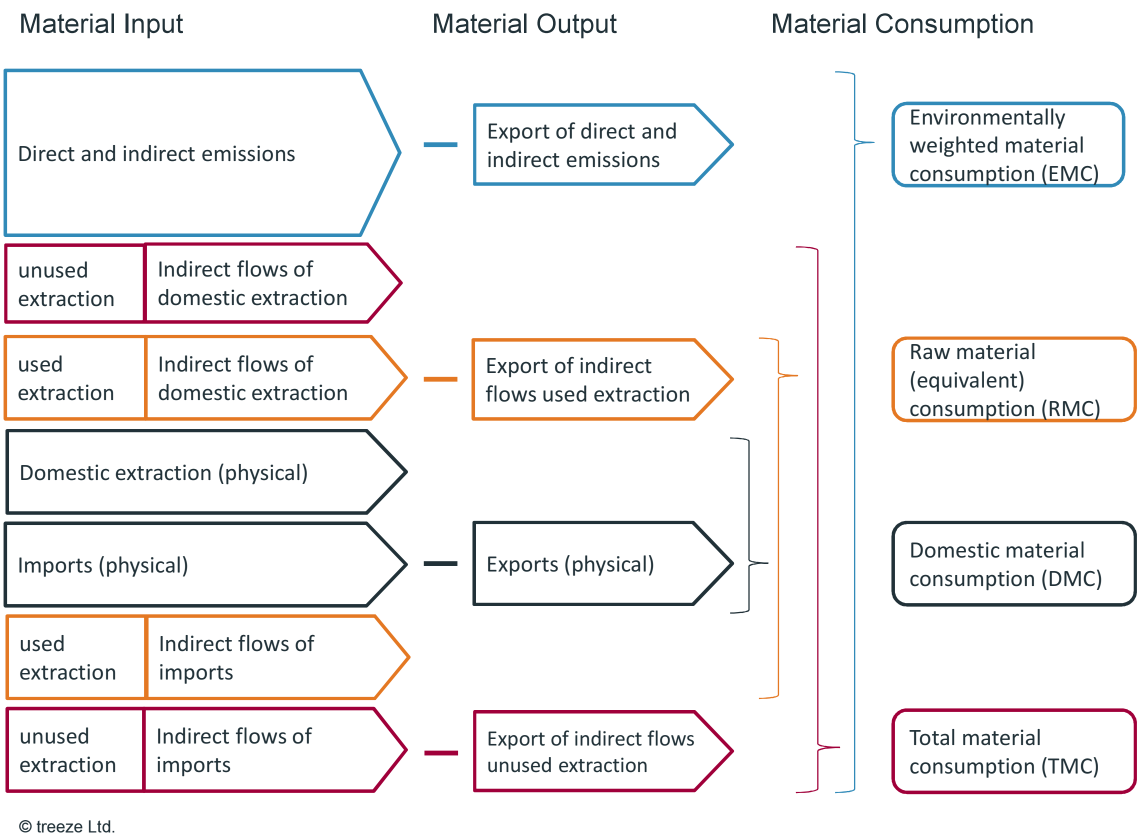


Fig. 6.1 Scope of different indicators (EMC, RMC, DMC and TMC) describing material consumption of regions and nations

6.2.2 Domestic material consumption (DMC)

The domestic material consumption assesses the direct consumption of materials caused by a country. The DMC is divided into the six main categories biomass, metals, non-metallic minerals, energy carriers, other products and wastes. The DMC is derived from the domestic material input (DMI) by subtracting the exported materials and goods. Indirect (grey) material uses are not part of the DMC and the DMI.

The DMC indicator is commonly published by the Swiss Federal Statistical Office (BFS 2011) and is measured in physical units of weight (kilograms or tons).

6.2.3 Domestic raw material consumption (RMC)

The domestic raw material consumption according to Schoer et al. (2012b) and Bringezu & Schütz (2010) measures the final domestic consumption of products in terms of raw materials used in the complete production chain of products consumed in a region or country.

The RMC includes indirect material demands that belong to the used extraction of materials. The used extraction includes materials which are needed for the production of goods like iron used in cars, buildings or roads, but excludes indirect flows of unused extracted materials like tailings in mining or unused organic residues like straw in agriculture.

The RMC is used in a pilot study in Germany (Schoer et al. 2012a) and is measured in physical units of weight (kilograms or tons).

6.2.4 Total material consumption (TMC)

The total material consumption assesses all the direct and indirect consumption of materials including the used and the unused extracted materials. Tailings from coal or metal mining and organic residues in agriculture are included in the total material consumption.

The total material requirement (TMR) is published by the Swiss Federal Statistical Office (FSO), on a yearly basis (BFS 2011). TMC as well as RMC currently are not. However, regarding the work which is being done in this regard, it may become part of the official material flow in a near future. The total material consumption is measured in physical units of weight (kilograms or tons).

6.2.5 Environmentally weighted material consumption (EMC)

The environmentally weighted material consumption (EMC) according to van der Voet (2009) is a hybrid indicator merging MFA and LCA. The assessed material flows are combined with life cycle based data on emissions and resource uses and evaluated using life cycle impact assessment (LCIA). Eleven different impact categories (global warming potential, ozone depletion potential, acidification, eutrophication, photochemical oxidation, abiotic depletion, human toxicity, freshwater ecotoxicity, terrestrial ecotoxicity, ionizing radiation, and land competition) are quantified. These eleven different environmental impact category indicators are based on CML midpoints (Guinée et al. 2001a) and are normalised with the annual flows in the World in the year 2000 (Wegener Sleeswijk et al. 2008). The normalised impact category indicator results are added without further weighting of the different categories. In other words: Each impact category has the same weight.

The EMC indicator is not used by any national statistical office and measured in dimensionless units. It is however recommended in a study about resource efficiency indicators published by the European Commission (Mudgal et al. 2012). The EMC's scope is comparable to several alternative methodologies like for example the ones published by JRC (EUBIA 2012) or by the FOEN (Frischknecht et al. 2009; Jungbluth et al. 2011).

6.3 Comparison of the indicators

6.3.1 Overview

The comparison of the different indicators is based on two levels. Firstly, a contribution analysis of the Swiss annual consumption of materials is carried out. Secondly, a set of materials was defined and the indicators are applied on the consumption of 1 kg of these materials. Finally, a correlation analysis based on the per kg results is carried out.

6.3.2 Comparison based on Swiss annual domestic material consumption

The contribution analysis of the different indicators is based on the annual domestic material consumption in Switzerland. The domestic material consumption is assessed in six different main categories, which are divided in further subcategories. The material uses reported in the domestic material consumption have been assigned to life cycle based data and direct and indirect resource and material uses, as well as direct and indirect emissions are calculated, depending on the indicator quantified.

While only the direct material use is included to quantify DMC, the direct material use and the extracted material used are included to quantify RMC. TMC is calculated including the direct and indirect material use and EMC includes the direct and indirect material use and the direct and indirect emissions.

The contribution of the different categories and subcategories of materials to the overall total are shown in Fig. 6.2. The contribution of the different categories and subcategories is compared to two endpoint life cycle impact assessment methods, namely ecological scarcity 2006 (Frischknecht et al. 2008) and ILCD endpoint recommended by the DG-JRC (EUBIA 2012).

The contribution of the different categories and subcategories to the overall total shows the following characteristics. In case of the DMC, RMC and TMC the consumption of non-metallic minerals has a high contribution to the overall result, because the mass of non-metallic minerals consumed like gravel or clay is very high. The share of non-metallic minerals diminishes from about 60 % (DMC) when extending the system boundary to include the extracted material used (RMC, 44 %) and to include all indirect material used (TMC, 33 %). The shares of “other products” and “metal products” are increasing when extending the system boundary.

In terms of environmental impacts, the consumption of non-metallic minerals is only of low importance. The three environmentally oriented indicators EMC, ecological scarcity 2006 and ILCD show shares of less than 5 %. The contributions of “other products”, “non-iron metals”, “iron and steel” (EMC only), “metal products” and “plant production” (ecological scarcity only) are substantially higher as compared to the mass based indicators DMC, RMC and TMC. The contribution of the categories “liquid and gaseous energy carriers” and “other fossil energy carriers” is similar for all indicators analysed.

The contribution of the different subcategories looks more similar when comparing the EMC and the two endpoint indicators ecological scarcity 2006 and ILCD. The contributions of the categories 4 (energy carriers) and 5 (other products) are of a similar size. However, the categories 1 (Biomass), 2.01 (iron and steel), 2.02 (non-iron metals) show different contributions between EMC on one side and the two endpoint indicators on the other.

The analysis of Fig. 6.2 leads to the conclusion that the DMC, RMC and TMC are not able to appropriately represent environmentally relevant material flows. EMC shows some similarities with the two endpoint indicators, although differences in case of several subcategories can be observed.

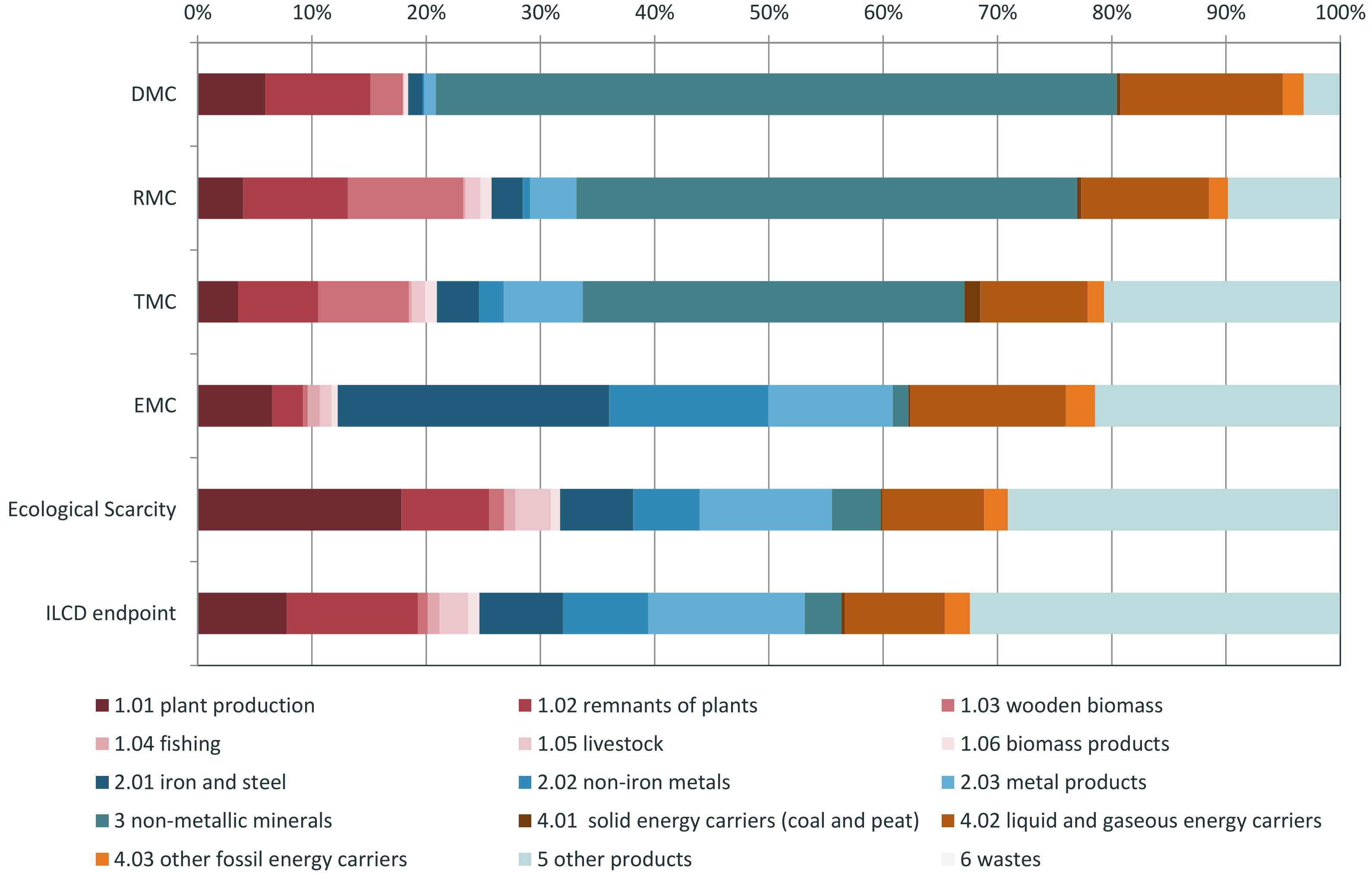


Fig. 6.2 Relative contribution of the different categories and subcategories of the Swiss domestic material consumption to the total score of the different indicators analysed
Other products include mainly chemical products, furniture and products made of plastics
red colours: biomass; blue colours: metals and minerals; brown/orange colours: fossil energy carriers

6.3.3 Comparison based on the consumption of 1 kg of various materials

Fig. 6.3 shows the comparison of the results of the different indicators applied to various materials of different material groups relative to a reference material. Reinforcing steel was selected as the reference material causing medium material uses and environmental impacts. The relative results are shown on a logarithmic scale.

A list of the different materials selected for the comparison is shown in Tab. 6.2. The selection includes representative materials from seven different groups of materials. The seven groups are minerals, biomass, energy carriers, plastics, chemicals, metals and precious metals. The base selection includes a total of 52 materials, which has been expanded for the analysis of impacts of Nitrogen to a total of 58 materials.

Tab. 6.2 Set of materials selected and the corresponding ecoinvent dataset for the comparison per kg of material sorted by group (additional materials for the chapter Nitrogen / Eutrophication are highlighted with grey colour)

Group	No	Material	ecoinvent dataset
Mineral	1	Basalt	basalt, at mine/RER U
	2	Cement	Cement, unspecified, at plant/CH U
	3	Clay	Clay, at mine/CH U
	4	Dolomite	Dolomite, at plant/RER U
	5	Gravel	Gravel, unspecified, at mine/CH U
	6	Gypsum	Gypsum, mineral, at mine/CH U
	7	Limestone	Limestone, at mine/CH U
	8	Sand	Sand, at mine/CH U
Biomass	9	Sawn timber	Sawn timber, hardwood, raw, air dried, u=20%, at plant/RER U
	10	Yarn, cotton	Yarn, cotton, at plant/GLO U
	11	Yarn, jute	Yarn, jute, at plant/IN U
	12	Yarn, kenaf	Yarn, kenaf, at plant/IN U
	13	Wheat	Wheat IP, at feed mill/CH U
	14	Maize	Grain maize IP, at farm/CH U
	15	Fava beans	Fava beans IP, at farm/CH U
	16	Potatoes	Potatoes IP, at farm/CH U
	17	Rape seed	Rape seed IP, at farm/CH U
	18	Rye grains	Rye grains IP, at farm/CH U
	19	Soy beans	Soy beans IP, at farm/CH U
	20	Sugar beets	sugar beets IP, at farm/kg/CH U
Meat	21	Poultry	poultry meat, IP, at slaughterhouse/kg/CH U
	22	Veal	veal, IP, at slaughterhouse/kg/CH U
	23	Lamb	lamb meat, IP, at slaughterhouse/kg/CH U
	24	Beef	beef, IP, at slaughterhouse/kg/CH U
	25	Pork	pork, IP, at slaughterhouse/kg/CH U
	26	Mixed meat	meat mixed, IP, at slaughterhouse/kg/CH U
Energy Carriers	27	Hard Coal	Hard coal, at regional storage/WEU U
	28	Lignite	Lignite, at mine/RER U
	29	Peat	Peat, at mine/NORDEL U
	30	Natural gas	Natural gas, at consumer/RNA U
	31	Light fuel oil	Light fuel oil, at regional storage/CH U
	32	Petrol	Petrol, unleaded, at regional storage/CH U
	33	Diesel	Diesel, at regional storage/CH U
Plastics	34	Nylon	Nylon 66, at plant/RER U
	35	PET	Polyethylene terephthalate, granulate, amorphous, at plant/RER U
	36	HDPE	Polyethylene, HDPE, granulate, at plant/RER U
	37	PP	Polypropylene, granulate, at plant/RER U
Chemicals	38	Ammonium nitrate	Ammonium nitrate, as N, at regional storehouse/RER U
	39	Triple superphosphate	Triple superphosphate, as P2O5, at regional storehouse/RER U
	40	Potassium nitrate	Potassium nitrate, as K2O, at regional storehouse/RER U
	41	Acetone	Acetone, liquid, at plant/RER U
	42	Benzene	Benzene, at plant/RER U
	43	Acetic acid	Acetic acid from acetaldehyde, at plant/RER U
	44	Glycerine	Glycerine, from epichlorohydrin, at plant/RER U
Metals	45	Steel	Reinforcing steel, at plant/RER U
	46	Lead	Lead, at regional storage/RER U
	47	Nickel	Nickel, 99.5%, at plant/GLO U
	48	Tin	Tin, at regional storage/RER U
	49	Titanium dioxide	Titanium dioxide, production mix, at plant/RER U
	50	Zinc	Zinc, primary, at regional storage/RER U
	51	Aluminium	Aluminium, production mix, at plant/RER U
	52	Copper	Copper, at regional storage/RER U
	53	Molybdenite	Molybdenite, at plant/GLO U
Precious metals	54	Palladium	Palladium, at regional storage/RER U
	55	Platinum	Platinum, at regional storage/RER U
	56	Rhodium	Rhodium, at regional storage/RER U
	57	Silver	Silver, at regional storage/RER U
	58	Gold	Gold, at regional storage/RER U

Compared to environmental impacts, the indicator DMC underestimates precious metals and metals and overestimates minerals, energy carriers and partly biomass. The results of the indicator RMC are systematically and substantially lower compared to the environmental impacts of precious metals and higher compared to the environmental impacts of minerals. TMC results are systematically higher compared to the environmental impacts of minerals, whereas they are more in line with the environmental impacts of precious metals. EMC results tend to follow the environmental impacts of materials, which is particularly true for minerals and (precious) metals.

Lignite (energy carrier) shows a particular pattern. Due to large amounts of overburdens, TMC of 1 kg lignite is relatively high compared to the TMC of other materials and compared to the environmental impacts related to lignite. Cement (listed under "minerals") shows rather similar indicator results. This is due to the energy and emission intensive burning process in cement kilns. Cotton yarn shows overproportional indicator results. On one hand, cotton cultivation causes substantial environmental impacts and on the other, the share of plant remnants is relatively high.

The impacts of minerals assessed with the indicators RMC and TMC are between one and two orders of magnitude higher than those assessed with the indicators that include environmental impacts. Combined with the high share of mass in the DMC, RMC and TMC this leads to an overestimation of the consumption of minerals as shown in Fig. 6.2.

The results in Fig. 6.3 confirm that the DMC, RMC and TMC are not able to appropriately capture the environmental impacts of the Swiss consumption.

One might consider using a selection of the subcategories of materials and apply DMC, RMC or TMC on such subsets. However, even within a subcategory "metals" the environmental intensities (environmental impacts per kg metal) of metals such as iron, nickel, gold or platinum differ substantially. A DMC, RMC or TMC indicator including all but mineral materials (such as sand and gravel) will show similar anomalities. The importance of wooden biomass for instance would substantially be overestimated.

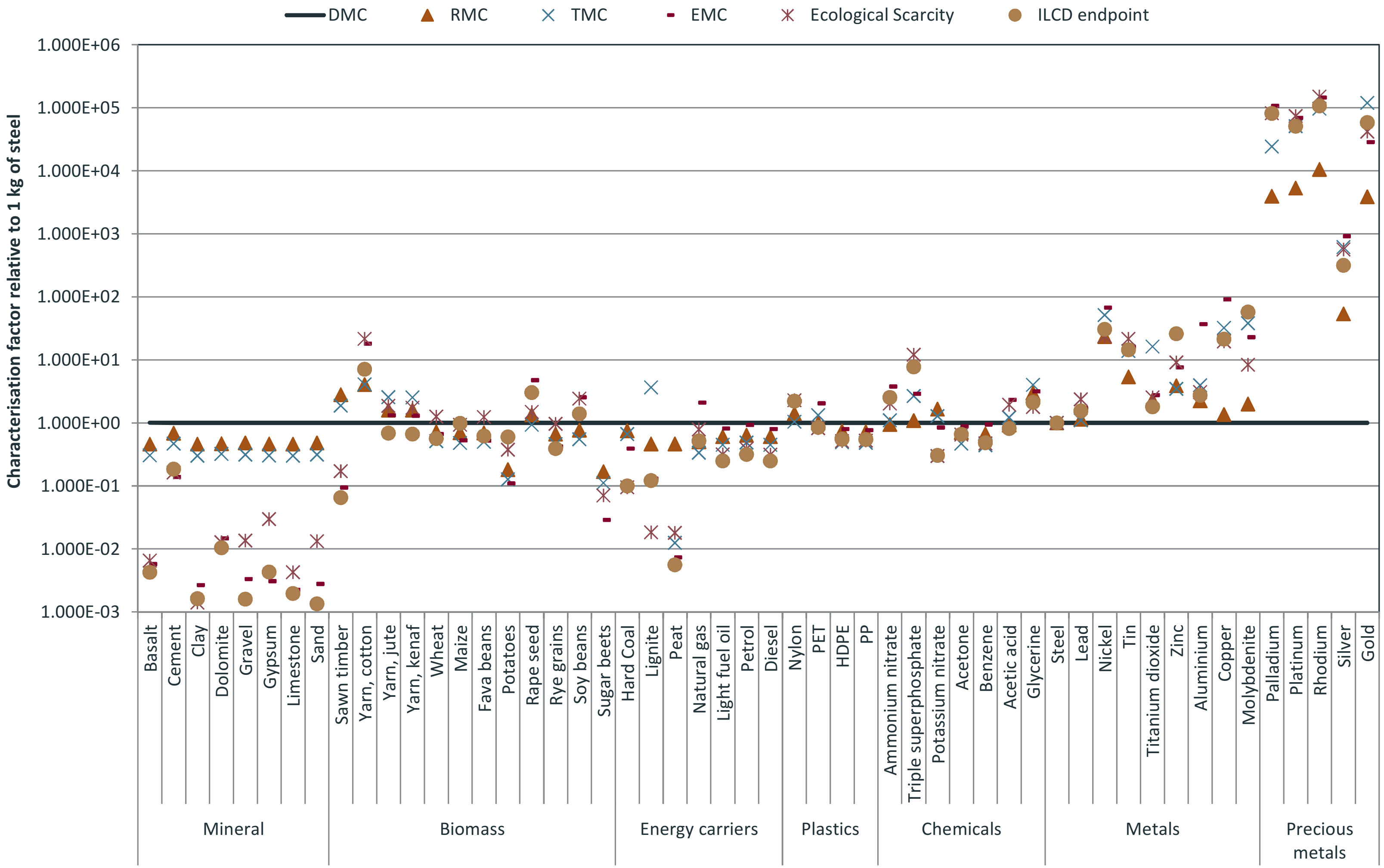


Fig. 6.3 Characterisation of selected materials for the different indicators analysed relative to the environmental impacts of 1 kg of reinforcing steel (logarithmic scale)

6.3.4 Correlation analysis

Tab. 6.3 shows the correlation coefficients of the different material indicators and the endpoint indicators of the total environmental impacts according to ecological scarcity and ILCD endpoint applied on the consumption of 1 kg of the materials shown in Fig. 6.3. Ecological scarcity and the ILCD impact assessment methods are used as up to date representatives of two very different impact assessment approaches, namely a distance to target approach and a damage oriented approach, respectively.

The correlation of the different indicators except the DMC is very high. However, the correlation analysis is dominated by the materials with high impacts like precious metals. The rather low correlation of the different indicators, when looking at non-metallic minerals is revealed in Fig. 6.2 and Fig. 6.3. Despite this, there is a good correlation between the indicators analysed, especially in case of the ecological scarcity method and ILCD endpoint, which show a correlation above 0.95 with all indicators except the DMC and TMC.

TMC shows a slightly lower correlation compared to RMC. This is mainly caused by the deviating values for precious metals and lignite. The extraction of these materials causes a high amount of unused material (overburden).

Tab. 6.3 Correlation coefficient of the indicators analysed for selected materials correlation coefficients above or equal to 0.90 are highlighted with dark grey colour; n.d.: not defined

Correlation coefficient	DMC	RMC	TMC	EMC	Ecological scarcity	ILCD endpoint
DMC	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
RMC		1.00	0.86	0.95	0.99	0.96
TMC			1.00	0.72	0.79	0.85
EMC				1.00	0.99	0.97
Ecological Scarcity					1.00	0.98
ILCD weighted						1.00

6.4 Evaluation of the indicators

6.4.1 Overview

Tab. 6.4 shows the summary of the evaluation of the four material use indicators analysed according to the scheme of the “True & Fair View” study (Schwegler et al. 2011). A detailed evaluation is shown in Appendix E.

The main differences between the indicators analysed occur in the environmental relevance, general view, transparency, communicability, and data availability.

Tab. 6.4 Comparison of the material use indicators according to the "True & Fair View" requirements; +: good performance; -: bad performance; +/-; both good and bad performance

Topic	Material use			
Indicator	DMC	RMC	TMC	EMC
Environmental relevance	-	+/-	+/-	+
Focus on the overall picture	-	+/-	+/-	+
Reliability	+	+	+	+
Transparency	+	-	-	+/-
Comprehensibility / communicability	+	+	+	+/-
Coherence and comparability	+	+/-	+/-	+/-
Availability of information: Data availability and quality	+	+/-	+/-	+
Timeliness (up-to-date information)	+	+	+	+
Ease of the implementation	+	+/-	+/-	+

6.4.2 Environmental relevance

The DMC shows a low environmental relevance because it does not include any indirect flows and because of the simple addition of the material weight does not distinguish between the environmental intensity of e.g. palladium on the one hand and gravel on the other. On average, the RMC and the TMC show a fair correlation with environmental impacts. However, the importance of the consumption of non-metallic minerals like gravel, sand or limestone, the environmental relevance is overestimated. The EMC has a higher environmental relevance since the correlation of the EMC and the ecological scarcity and the ILCD endpoint is good for all groups of materials. However, the EMC still shows a different contribution of the different main categories of the DMC shown in Fig. 6.2.

The main scientific deficit of the EMC lies in the unweighted aggregation of the impact category indicator results, which implies identical environmental damages caused by the individual impacts such as climate change, tropospheric ozone creation, eutrophication and so on (see also Nathani & Jungbluth 2012). The iron & steel and non-iron metals have a considerably higher contribution compared to ecological scarcity and ILCD endpoint, mainly based on the high contribution of human toxicity and ionizing radiation in case of the EMC indicator according to van der Voet (2009). Nevertheless, EMC is the indicator which represents the environmental relevance of material consumption most appropriately.

6.4.3 Focus on the overall picture

All indicators use a single indicator to quantify the material consumption. However, the DMC is not life-cycle based and excludes indirect material uses and emissions. The RMC and the TMC both consider indirect material uses but exclude indirect emissions. The EMC is the only indicator including the indirect material uses and emissions over the full life cycle. Thus the EMC is able to represent the most complete picture.

6.4.4 Reliability

All indicators (concepts) are reliable, have a solid scientific basis and are published. The calculations do not include value choices but assess material use. However, the concepts of the indicators themselves include value choices (e.g. the selection of the impact categories and the unweighted aggregation in case of the EMC or the exclusion of non-used materials in RMC). Hence, there is no difference in reliability between the indicators analysed.

6.4.5 Transparency

The results of all indicators are published, transparent and can be reproduced. However, the modelling and calculations of the RMC, TMC and EMC are more complex compared to the DMC. TMC calculations additionally required manual adjustments within the ecoinvent data.

6.4.6 Comprehensibility (communicability)

Material use is commonly associated with weight. The indicators DMC, RMC and TMC quantify kilograms of material used whereas the EMC is expressed in a dimensionless number, which corresponds to the sum of the eleven impact categories normalised with the total emission in the year 2000. Because of its virtuality this dimensionless number is more difficult to understand.

6.4.7 Coherence and comparability

The indicators analysed show a high level of coherence and comparability. It is highest for the DMC because of its simple nature. Characterisation factors may change with respect to the indicators RMC, TMC and EMC. Such changes would entail a recalculation of the time series.

6.4.8 Availability of information (data availability and quality)

DMC data are readily available for Switzerland. In order to calculate the RMC, TMC and the EMC a linking of the direct material consumption with life cycle assessment data is needed. The data needed for this calculation are available.

6.4.9 Timeliness (up-to-date information)

Yearly data on the DMC are published for Switzerland by the FSO. Swiss RMC data are not available whereas a pilot study for the European Union has been completed in 2012. Swiss TMC and EMC data are currently not available but can be calculated combining DMC and life cycle assessment data.

6.4.10 Ease of the implementation

The implementation of DMC is rather straightforward. The implementation of RMC and TMC is more complicated, because the used (RMC) and additionally the unused (TMC) extracted material (like tailings) have to be included. The indicators needed for the quantification of the EMC are implemented in common LCA software and databases. Hence, one needs to link life cycle assessment data to the direct material consumption to calculate RMC, TMC and EMC.

The main challenge in the implementation lies in the mapping of the material flow accounts with life cycle assessment data. The material flows need to be disaggregated in order to enable a proper mapping of the material flows and life cycle inventory data.

6.5 Recommendation

If no traditional endpoint indicator like ecological scarcity or ILCD should be applied, we recommend the use of the environmentally weighted material consumption (EMC). Mass-based indicators like the DMC, RMC or TMC are not or much less able to give a full picture of the environmental impacts of material consumption. Materials with a high share in terms of weight, like gravel, have a very high contribution to DMC, RMC or TMC, but cause only small environmental impacts.

In case emission related indicators are considered inappropriate, the TMC and RMC show the next best approximation to the consumption of environmentally relevant materials. Despite its lower correlation with environmental indicators we recommend the use of the TMC because a similar indicator, the total material requirement (TMR) is already used by the Swiss Federal Statistical Office. However, it must be kept in mind that TMC (and RMC) strongly overestimate the environmental impacts of minerals.

6.6 Application of the indicator and double counting

The material use indicators follow a concept different from the concept of the other indicators discussed in this study. Water use, land use, air pollution and nitrogen fixation quantify the extraction (or use) of a resource and the release of pollutants irrespective of a specific product or service. The material consumption indicators discussed in this Chapter quantify the mass (amount) of material consumed (directly, and partly indirectly). The consumption of these amounts of materials lead to manifold environmental impacts, which comprise land use (due to e.g. the consumption of durum wheat), water use (due to e.g. the consumption of cotton textiles), air pollution (due to e.g. the consumption of copper) or nitrogen fixation (due to e.g. the consumption of mineral fertilisers).

It is therefore recommended to use the materials consumption indicator separately from the other indicators. While the indicators land use, water use, air pollution and nitrogen fixation (as well as climate change and ozone depletion) are complementary and may be used side by side, the EMC or TMC indicator is overlapping the other indicators and should be used alternatively.

7 Synthesis and Outlook

7.1 Synthesis

This study recommends environmental indicators, which help to analyse environmental impacts from a demand perspective, including the impacts abroad. They should be able to quantify environmental impacts in the course of the past 15 years as well as in the years to come and thereby contribute to monitor the effectiveness of measures taken by the Swiss government towards a green economy.

The set of environmental indicators used to quantify the environmental impacts of Swiss consumption should comply with the "True and Fair" principles (Schwegler et al. 2011) and thus be relevant with regard to the decisions to be taken and focus on the overall picture (including all relevant environmental impacts).

The five indicators recommended cover the following topics:

- Water stress indicator according to the Pfister midpoint:
  The water stress indicator is used as a proxy for impacts on resources, human health and ecosystems due to consumptive water use. It offers a regionally differentiated assessment.
- Biodiversity damage potential due to land use according to de Baan & Olson:
  The biodiversity damage potential quantifies the biodiversity loss due to a variety of land uses in different world biomes. It offers a regionally differentiated assessment.
- Particulate matter formation according to ReCiPe midpoint:
  The particulate matter formation indicator is used as a proxy for impacts on human health due to air pollution.
- Marine eutrophication according to ReCiPe midpoint:
  Marine eutrophication is used as indicator for eutrophying impacts on the marine environment caused by nitrogen emissions to air, water and soil.
- Consumption of environmentally relevant materials (EMC):
  The EMC is used as a proxy for the overall environmental impacts caused by material consumption in a country (Switzerland). If emission related indicators are considered inappropriate, the TMC indicator shows the next best approximation of the consumption of environmentally relevant materials. However it must be kept in mind that TMC strongly overestimates non-metallic minerals.

The five indicators quantify consumption or consumption related environmental impacts on very different levels. The water stress and the marine eutrophication indicators are midpoint indicators. The water stress indicator is supposed to represent a large variety of different impacts on human health, ecosystems and resources whereas marine eutrophication mainly addresses eutrophying impacts and thus impacts on ecosystems only.

Particulate matter formation is a midpoint indicator too. It is responsible for a large share of human health damages due to air pollution and thus may be considered to be close to an endpoint indicator.

The land use indicator “biodiversity damage potential” is an endpoint indicator addressing one of the main environmental threats to nature, biodiversity.

The material consumption indicator is a cross-cutting indicator, covering a large variety of environmental impacts (caused by material consumption). Hence, this indicator interferes and overlaps with the other four indicators discussed in this report and further indicators such as the global warming potential (climate change impacts).

The four impact related indicators recommended in this report and the climate change indicator (global warming potential) are suited to be used together. They address different environmental impacts and safeguard subjects. They all focus on environmentally relevant issues and they are relevant to decisions in view of a Green Economy.

7.2 Comparison to indicators recommended by the EU

In 2011, the European Joint Research Center in Ispra published a recommended set of environmental indicators (Hauschild et al. 2011). It covers twelve environmental topics ranging from climate change to ionising radiation. The land use and water use indicators recommended here differ from the recommendation of Hauschild et al. (2011) because recent scientific developments are taken into account. The marine eutrophication indicator is recommended in both studies. The recommendation with regard to air pollution (respiratory inorganics or particulate matter formation) differ because of the requirement of using physical measures as far as possible in the Swiss case, whereas Hauschild et al. (2011) recommend a method which takes intake fractions (share of pollutants inhaled and incorporated by humans) into account.

Finally, environmentally weighted material consumption (EMC) lies outside the traditional impact category framework used in life cycle assessment. The EMC indicator is however a recommended resource efficiency indicator of the European Commission (Mudgal et al. 2012). Other indicators recommended by Mudgal et al. 2012 differ from the ones recommended in this study and by Hauschild et al. (2011). This is particularly true for water and land use.

The European Commission published an overall environmental indicator (EUBIA 2012) based on the recommended set of indicators (Hauschild et al. 2011). This overall environmental indicator of the European Commission is closer to the ecological scarcity method 2006 than to the EMC indicator.

The indicators presented here are partly identical but partly also different from those recommended by JRC (see also Tab. 7.1). Our recommendations can be seen as a further development, and as a contribution to the international discussion on quantifying the environmental impacts of consumption.

With the four recommended impact related indicators and climate change we cover 5 of the 9 planetary systems for which Rockström et al (2009b) propose a safe operating space. Phosphorous, ocean acidification, stratospheric ozone depletion and chemical pollution are not yet covered.

Tab. 7.1: Comparison of the indicators recommended in this study and by the European Commission (Hauschild et al. 2011)

Name	This study	Study commissioned by European Commission
Water use	Water stress index (Pfister et al. 2009)	Ecological scarcity method 2006 (Frischknecht et al. 2006; Frischknecht et al. 2009)
Land use	Biodiversity damage potential (de Baan et al. 2012), combined with Olson et al. 2001	Soil organic matter according to Milà i Canals et al. (2007c)
Air pollution	Particulate matter formation (Goedkoop et al. 2009)	Respiratory inorganics, including fate and exposure (Greco et al. 2007)
Eutrophication / Nitrogen fixation	Marine eutrophication (Goedkoop et al. 2009)	Marine eutrophication (Goedkoop et al. 2009)
Environmentally relevant materials	Environmentally Weighted Material Consumption (van der Voet et al. 2009)	Environmentally Weighted Material Consumption (van der Voet et al. 2009)[1]

[1]: recommended by Mudgal et al. (2012)

7.3 Outlook

The following environmental impacts of global or national concern or environmental issues are not covered by the indicators discussed in this report (see also Fig. 7.1).

- acidification (natural environment)
- ecotoxicity (natural environment)
- cancer and non-cancer toxicity (human health)
- ionising radiation (human health)
- noise, in particular due to transport activities (human health)
- depletion of biotic resources (resources)

- depletion of mineral and energy resources (resources)
- radioactive waste (waste / human health)[12]

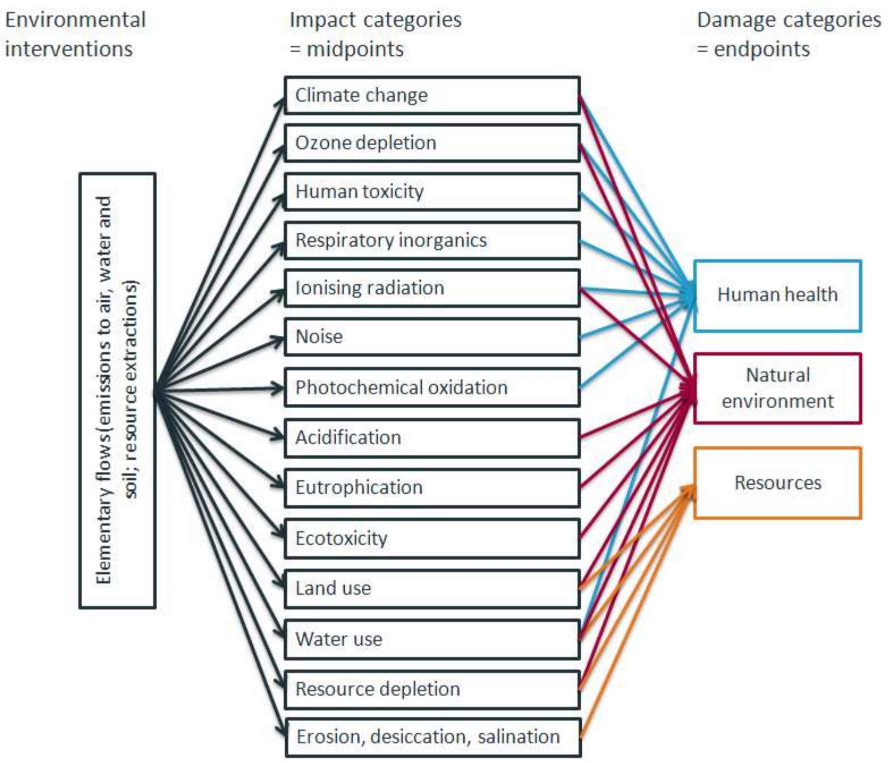


Fig. 7.1 Life cycle impact assessment environmental intervention – midpoint – damage framework

Ecotoxicity, noise and nuclear waste are considered the most important environmental impacts not yet covered by the indicators discussed in this report (and including climate change). Reduced availability, lower quality and large variability in data are main challenges with regard to toxicity related environmental impacts and to impacts on human health caused by noise. Nevertheless, it is recommended to evaluate them in a next phase.

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12 Radioactive waste is not listed as an endpoint in Fig. 7.1. Radioactive waste is not an environmental intervention, but the emissions from final repositories would be. However, leading LCI databases do not report (long-term) emissions from final repositories. That is why we list radioactive waste separately.

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A Appendix: Water

Tab. A.1 Detailed comparison of the water use indicators according to the "True & Fair View" requirements (Schwegler et al. 2011); +: good performance; -: bad performance; +/-; both good and bad performance

Characteristics	Frischknecht et al.		Milà I Canals & Raskin		Mila I Canals & Smakhtin		Water footprint Hoekstra		Pfister midpoint (WSI)	
Environmental relevance	+	withdrawal-to-availability ratio is a good indicator for the stress on the water resources, but ecosystems quality and human health effects are only insufficiently assessed	+	According to the authors the indicator is focused on the ecosystems quality using a withdrawal-to-availability ratio. This ratio does not describe a particular cause-effect chain and is more suitable to assess the impacts of the use of water resources	+	According to the authors the indicator is focused on the ecosystems quality using a withdrawal-to-availability ratio including EWR. This ratio does not describe a particular cause-effect chain.	- +	Three indicators, "green", "blue" and "grey" consumptive water use, are shown in three disaggregated results. Scarcity indexes are calculated on the basin level but the water flows are not characterised leading to a low environmental relevance. Spatial differentiation possible, not developed specifically for LCA but compatible.	+	withdrawal-to-availability ratio is a good indicator for the stress on the water resources, but ecosystems quality and human health effects are only insufficiently assessed. Multiannual effects like droughts are considered with the storage capacities in the calculation of the characterisation factors
Focus on the overall picture	+	The method uses a single indicator to quantify the water scarcity based on the availability of freshwater with a spatial differentiation on basin or country level. According to the authors the method does not focus on a specific AoP but is a good proxy indicator for stress on water resources	+	The method uses a single indicator to quantify the water scarcity based on the availability of freshwater with a spatial differentiation on basin or country level. According to the authors the method is an indicator to assess ecosystems quality, but according to our opinion the method is a better proxy indicator for stress on water resources as ecosystems quality and water resources	+	The method uses a single indicator to quantify the water scarcity based on the availability of freshwater with a spatial differentiation on basin or country level taking into account the environmental water requirement. According to the authors the method is an indicator to assess ecosystems quality.	+	The method uses three indicators to quantify the blue, green and grey water use based on the consumption of "blue" and "green" and the pollution of "grey" water on any spatial differentiation. According to the authors the method does no cover a specific AoP	+	The method uses a single indicator to quantify the water scarcity based on the availability of freshwater with a spatial differentiation on basin, country or 0.5° grid cell level. According to the authors the method is a good proxy indicator for the stress on water resources and to a lesser extent to the human health
Reliability	+	The method is based on a rudimentary environmental model. The indicator is based on a scarcity indicator which does not reflect a particular cause-effect chain and units cannot be compared with other indicators (m^3-eq)	+	The method is scientifically sound and has a high reliability and credibility. However,the indicator is based on a withdrawal-to-availability ratio which does not reflect a particular cause-effect chain and units cannot be compared with other methods (m^3-eq)	+	The method is scientifically sound and has a high reliability and credibility. However,the indicator is based on a withdrawal-to-availability ratio which does not reflect a particular cause-effect chain and units cannot be compared with other methods (m^3-eq). The consideration of the environmental water demand is an advantage compared to indicators which take only availability and withdrawal into account.	+	The method is scientifically sound and has a high reliability and credibility. The indicator is based on three waterfootprints which do not reflect a particular cause-effect chain but the physical unit of a water volume is easy to understand	+	The method is scientifically sound and has a high reliability and credibility. However, the indicator is based on a withdrawal-to-availability ratio which does not reflect a particular cause-effect chain and units cannot be compared with other methods (m3eq)
Transparency	+	The method is easy to understand and the calculations are transparent and published and can be reproduced based on the data available in the aquastat database.	+	The method is easy to understand and the calculations are transparent and published and can be reproduced based on the data available in the aquastat database.	+/-	The method is easy to understand and the calculations are accessible and published, but cannot be reproduced (WATERGAP2, GIS needed).	+/-	The method is easy to understand and the calculations are transparent and published, but characterisation factors are only available only for blue water scarcity for major watersheds, and cannot be reproduced for the "blue" and "green" water scarcity and "grey" water pollution	+/-	The method is difficult to understand and the calculations are accessible and published, but cannot be reproduced (WATERGAP2, GIS needed).
Comprehensibility (communicability)	+/-	The communicability of the indicator is good, since it is only one number but the virtuality of an equivalent is difficult to understand	+/-	The communicability of the indicator is good, since it is only one number but the virtuality of an equivalent is difficult to understand	+/-	The communicability of the indicator is good, since it is only one number but the virtuality of an equivalent is difficult to understand	+/-	The communicability of the indicator is medium, since there are three numbers abut the physical unit of a water volume is easy to understand	+/-	The communicability of the indicator is good, since it is only one number but the virtuality of an equivalent is difficult to understand
Coherence + Comparability	+/-	Comparability of the times series is given but has to be recalculated if there is a change in the characterisation factors (withdrawal and availability). Comparability between different countries is given because the same data source is used. Comparability between the different indicators is not given because different data sources are used depending on the indicator (AQUASTAT und WaterGAP2)	+/-	Comparability of the times series is given but has to be recalculated if there is a change in the characterisation factors (withdrawal and availability). Comparability between different countries is given because the same data source is used. Comparability between the different indicators is not given because different data sources are used depending on the indicator (AQUASTAT und WaterGAP2)	+/-	Comparability of the times series is given but has to be recalculated if there is a change in the characterisation factors (withdrawal and availability and the environmental water requirement). Comparability between different countries is given because the same data source is used. Comparability between the different indicators is not given because different data sources are used depending on the indicator (AQUASTAT und WaterGAP2)	+/-	Comparability of the times series is given and does not have to be recalculated because no weighting / characterisation is applied. Comparability between the different indicators is not given because different data sources are used depending on the indicator (AQUASTAT und WaterGAP2)	+/-	Comparability of the times series is given but has to be recalculated if there is a change in the characterisation factors (withdrawal and availability of water and variation factor for flow regulated basins). Comparability between different countries is given because the same data source is used. Comparability between the different indicators is not given because different data sources are used depending on the indicator (AQUASTAT und WaterGAP2)
Availability of information: Data availability and quality	+	reliable data on water consumption, withdrawal and availability are available on country level (AQUASTAT)	+	reliable data on water consumption, withdrawal and availability are available on country level (AQUASTAT)	+/-	no reliable data on water consumption, withdrawal and availability are available on the basin level (AQUASTAT), WATERGAP 2 model used for the calculations on 0.5°*0.5° grid scale, data on the environmental water requirement (EWR) are not available on the country level, only on the basin level, the characterisation factors have to be aggregated from basin to country scale	+/-	no reliable data base on blue, green and grey water use is available on country and basin level	+	no reliable data on water consumption, withdrawal and availability are available on the basinlevel (AQUASTAT), WATERGAP 2 model used for the calculations on 0.5°*0.5° grid scale, data on flow regulation only available on the basin level, the characterisation factors have to be aggregated to basin or country scale
Timeliness (up-to-date information)	+	Updated for 2013	+	Published in 2009 and 1997	+/-	Published in 2009 and 2004	+	Published in 2011	+	Published in 2009
Ease of the implementation	+/-	Adjustments of the ecoinvent database are required (consumptive use only, regionalisation or water scarcity classes). Foreground data needs to specify consumptive share of water use and indicate geographical location or water scarcity class.	-	Adjustments of the ecoinvent database are required (consumptive use only and regionalisation of the water use). Foreground data needs to specify consumptive share of water use and indicate geographical location.	-	Adjustments of the ecoinvent database are required (consumptive use only and regionalisation of the water use). Foreground data needs to specify consumptive share of water use and indicate geographical location.	- +	Adjustments of the ecoinvent database are required (blue and green water consumptive use only and grey water pollution and regionalisation of the blue, green and grey water use). Foreground data needs to specify consumptive share of blue and green water use and grey waterpollution and indicate geographical location. Method has to be implemented in LCA Software and Methodology.	+/-	Adjustments of the ecoinvent database are required (consumptive use only and regionalisation of the water use). Foreground data needs to specify consumptive share of water use and indicate geographical location.

B Appendix: Land Use

Tab. B.1 Part 1 of the detailed comparison of the land use indicators according to the "True & Fair View" requirements (Schwegler et al. 2011); +: good performance; -: bad performance; +/-; both good and bad performance

Characteristics	Lugschitz		Ecological footprint		Köllner		deBaan & Olson		Mila I Canals	
Environmental relevance	-	land demand per capita is a good indicator for the actual land demand but forgoes information on the productivity and biodiversity of the different biomes / ecosystems	+	average potential productivity is a valid impact pathway for the assessment of land use based on nine different land use types	+	plant species richness is a valid impact pathway for the assessment of land use divided in categories urban, agricultural, forested and other are (total of 58 subcategories) based on ecological damage potential (EDP)	+	plant species richness is a valid impact pathway for the assessment of land use based on biodiversity damage potential (BDP) relative species richness is a good indicator for biodiversity-related land use impacts	+	This method considers Soil Organic Matter (SOM) as a soil quality indicator. SOM is qualified as a keystone soil quality indicator, especially for assessing the impacts on fertile land use (agriculture and forestry systems).
Focus on the overall picture	+/-	The method uses a single indicator to quantify the actual land demand, the type of the land use is not differentiated	+/-	The method uses a single indicator to quantify the land use based on the bioproductivity distinguishing nine different land use types	+/-	The method uses a single indicator to quantify the loss of plant species richness based on the ecological damage potential with a spatial differentiation on the biome level	+	The method uses a single indicator to quantify the biodiversity damage potential (BDP) based on the loss of relative species richness for 8 land use types and up to 13 biomes with aggregated global values for all land use types	+/-	However, it must be noted that in LCIA it should be combined with biodiversity indicators. In highly acidified or waterlogged soils the SOM may not correlate directly with soil quality. on fertile land use (agriculture and forestry systems).
Reliability	+	The method is based on a rudimentary environmental model. The indicator is based on the actual land demand which does not reflect a particular cause-effect chain	+	The method is scientifically sound and has a high reliability and credibility. However,the indicator is based on bioproductivity which does not reflect a particular cause-effect chain and units cannot be compared with other methods (global hectares-eq)	+	The method is scientifically sound and has a high reliability and credibility. However, the indicator is based on ecological damage potential (EDP) which does not reflect a particular cause-effect chain and units cannot be compared with other methods (Urban area-eq)	+	The method is scientifically sound and has a high reliability and credibility. However,the indicator is based on relative species richness which does not reflect a particular cause-effect chain and units cannot be compared with other methods (not-used-forest-eq)	+	The method is scientifically sound and has a high reliability and credibility. The indicator is based on soil organic matter which does reflect a particular cause-effect chain and can be monitored and measured.
Transparency	+	The method is easy to understand and the calculations are transparent and published.	+	The method is easy to understand and the calculations are transparent and published.	+/-	The method is of medium difficulty to understand and the calculations are transparent and published.	+/-	The method is of medium difficulty to understand and the calculations are accessible and published.	+	The method is easy to understand and the calculations are accessible and published.
Comprehensibility (communicability)	+	The communicability of the indicator is good, since it is only one number and describes a physical unit.	+/-	The communicability of the indicator is good, since it is only one number and is related to the actual land demand ut the virtuality of an global ha-eq is difficult to understand	+/-	The communicability of the indicator is good, since it is only one number but the virtuality of an urban area-eq is difficult to understand.	+/-	The communicability of the indicator is good, since it is only one number but the virtuality of an (semi)natural forest equivalent is difficult to understand	-	The communicability of the indicator is good, since it is only one number, but C deficit difficult to understand
Coherence + Comparability	+	Comparability of the times series is given since there is no change in the factors.	+/-	Comparability of the times series is only given if there is no change in the database and impact factors.	+/-	Comparability of the times series is only given if there is no change in the database and impact factors.	+/-	Comparability of the times series is only given if there is no change in the database and HANPP factors.	+/-	Comparability of the times series is only given if there is no change in the database and impact factors.
Availability of information: Data availability and quality	+	no special data needed for the calcualtion of the characterisation factors	+/-	reliable data on Global Agro-Ecological Zones (GAEZ) by the International Institute for Applied Systems Analsis (IIASA) and Food and Agriculture Organization (FAO) are basis of the equivalence-factors	+	data on the ecological damage potential difficult to obtain, Köllner & Scholz 2007 is the only source, no database for ecological damage potential of the different biomes	+	GLOBIO3 data base, BDM database, no easy access	+	a) measured directly from soil samples, (b) calculated using local datasets and locally adjusted models, and (c) estimated from literature values for different areas and crops (ISRIC-WISE soil database)
Timeliness (up-to-date information)	+	published in 2011 and 2001	+	Published in 2009 and 2004	+	Published in 2001 and 2008	+	published in 2012	+	published in 2007
Ease of the implementation	+	ready to use, data needed is implemented in ecoinvent	+	implemented in ecoinvent background data	+	no differentiation of biomes in ecoinvent background data, regionalisation of the biomes in foreground is possible, in addition biome 5 als world average values are compatible with ecoinvent background data	+/-	no differentiation of biomes in ecoinvent background data, regionalisation of the biomes in foreground is possible, in addition aggregated global values are compatible with ecoinvent background data	+/-	easy to implement, no regionalisation and thus no adaptation of ecoinvent background data necessary

Tab. B.2 Part 2 of the detailed comparison of the discarded land use indicators according to the “True & Fair View” requirements (Schwegler et al. 2011); +: good performance; -: bad performance; +/-; both good and bad performance

Characteristics		Haberl HANPP		Baitz		Weidema		Köllner 2007a&b		Köllner 2001
Environmental relevance	+	HANPP is an aggregated indicator that reflects both the amount of area used by humans and the intensity of land use. HANPP measures to w hat extent land conversion and biomass harvest alter the bioproductivity of ecosystems. It is a prominent measure of the “scale” of human activities compared to natural processes	+	Characterisation model includes seven different land use effects. Only local effects are considered.	+	Characterisation model based on species richness, ecosystem scarcity and ecosystem vulnerability combined in one indicator	-	Plant species richness of Sw itzerland based on ecological damage potential (EDP). Plant species richness is a valid impact pathw ay for the assessment of land use.		same as Köllner 2007, Köllner 2007 used some actual publications (1985-2004, Köllner 2001 used data until 1999) on species richness and had more dta available (3706 in 2001 compared to 5581 sample plots in 2007)
Focus on the overall picture	+	The method uses a single indicator to quantify the extent land conversion and biomass harvest alter the bioproductivity of ecosystems on a spatial differentiation 0.5° grid cell level	+	Seven different indicators describing soil quality. Most data must be collected by the practitioner. When no site-specific data are available, country-average data are used.	+	The method uses a single indicator based on the loss of relative species richness combined w ith ecosystem vulnerability and scarcity	+	The method uses a single indicator to quantify the loss of plant species richness based on the ecological damage potential w ith the reference of Sw iss Low land. EDP can be assessed in a linear and non-linear w ay. The method refers to Sw itzerland only.		
Reliability	+	The method is scientifically sound and has a high reliability and credibility. How ever, the indicator is based on bioproductivity w hich does not reflect a particular cause-effect chain	+	The method is scientifically sound and has a high reliability and credibility. How ever,the method is based on seven indicators w hich do not reflect a particular cause-effect chain, cannot be aggregated and units cannot be compared w ith other methods	+	The method is scientifically sound and has a high reliability and credibility. How ever,the indicator is based on relative species richness, ecosystem scarcity and vulnerability w hich do not reflect a particular cause-effect chain and units cannot be compared w ith other methods	+	The method is scientifically sound and has a high reliability and credibility. The indicator considers vascular plants only. How ever,the indicator is based on relative species richness w hich does not reflect a particular cause-effect chain.		
Transparency	+/-	The method is difficult to understand and the calculations are transparent and published.	+/-	The method is difficult to understand and the calculations are accessible and published.	+/-	The method is difficult to understand and the calculations are accessible and published.	+/-	The method is difficult to understand and the calculations are accessible and published.		
Comprehensibility (communicability)	+/-	The communicability of the indicator is good, since it is only one number but the virtuality of an equivalent is difficult to understand	+/-	The communicability of the indicator is bad, since it is there are seven different indicators, w hich cannot be aggregated and are difficult to understand	+/-	The communicability of the indicator is good, since it is only one number but the virtuality of an equivalent is difficult to understand	+	The communicability of the indicator is good, since it is only one number.		
Coherence + Comparability	+/-	Comparability of the times series is only given if there is no change in the database and HANPP factors.		?????	+/-	Comparability of the times series is only given if there is no change in the database and impact factors.	+/-	Comparability of the times series is only given if there is no change in the database and impact factors.		
Availability of information: Data availability and quality	-	GIS database on land use and land cover needed		?????		biome2 model,	+	EDP fully published		
Timeliness (up-to-date information)	+	Published in 2009		published in 2001, updated 2008		published in 2001	+	Published in 2007 and 2001		
Ease of the implementation	-	not implemented in ecoinvent background data, assessments of HANPP based on LCA methods are feasible, but considerable conceptual and data challenges still have to be overcome for this approach to become operational					+/-	easy to implement, no regionalisation and thus no adaptation of ecoinvent background data necessary		

Tab. B.3 Part 3 of the detailed comparison of the discarded land use indicators according to the “True & Fair View” requirements (Schwegler et al. 2011); +: good performance; -: bad performance; +/-; both good and bad performance

Characteristics	Feldwisch et al 2006		Staub et al. 2011		Frick 2012		Roth et al 2010		ReCiPe midpoint	
Environmental relevance	+	Feldwisch et al (2006) presents a strategy plan to decide which areas can be used for which purposes on a very regional scale (community/city).	+	Contribution of the ecosystem to welfare. Includes not only land use but also water and air quality issues.	+/-	Interviews how people experience landscape in terms of structure, character, fascination, authenticity, beauty, quality and local binding.	+/-	The study gives an overview of the state and development of the Swiss landscape based on the DSIPR model.	-	Uses the competition approach, i.e. all different types of land uses are added. Three midpoint categories are introduced (agricultural land occupation, urban land occupation, natural land transformation)
Focus on the overall picture	+	For every parcel the soil functions (living environment, ecosystem, buffer, archival) are rated individually and summarized in an endpoint. The endpoint is assessed in different ways depending on the scope. As a result it can be decided which parcels deserve protection.	-	no CFs, only qualitative statements, land use and land quality (biodiversity) is part of several indicators.	+/-	The study gives a very subjective view of the landscape.	+/-	The study considers indicators such as population, living area, private transport, sealing, skilift, agriculture, etc.	-	No quality aspects are considered, only the area.
Reliability	+/-	The rating within the different soil functions is scientifically sound. The unavoidable weighting of the soil functions to one statement is similar to the weigthing of LCA endpoint method.			+/-	The method is scientifically sound in terms of subjective parameters such as aesthetics or character and fascination of the landscape. However, especially with regard to the assessment of landscape quality, measurements of physical and chemical soil parameters are considered to be more appropriate.	+	The study is considered to be scientifically sound.	+/-	reliable in case of area but not useful to assess biodiversity
Transparency	+	The concept of rating and summarizing is of easy difficulty to understand and the calculations are transparent and published.			+	The method is easy to understand.	+	The method is easy to understand.	+	the method is easy to understand
Comprehensibility (communicability)	-	The communicability of the indicator is good, since it is only one number.			+	The communicability of the results is easy.	+	The communicability of the single indicators is of easy difficulty.	+	easy communication as only area is summed up
Coherence + Comparability	+/-	Comparability of the times series is only given if there is no change in the database and impact factors.			+/-	Comparability is given if interviews are conducted regurarly and at the same sites.	+/-	Comparability is given within time series and with other countries using the same method (DSIPR).	+/-	comparability is given if interviews are conducted regurarly at the same sites.
Availability of information: Data availability and quality	+/-	Unclear if all 70 publications are available which are necessary to do the rating within one soil function.			-	Raw data are so far not available. Unclear when study will be published.	+	Data are available.	+	data available
Timeliness (up-to-date information)	+/-	Main studies are published in 2003, 2006, and 2007. However, some underlying studies necessary for the rating of the individual soil functions seem to be out-dated.	+	published in 2011	+/-	study have not been published yet	+	published in 2010	+	published in 2007
Ease of the implementation	-	characterisation factors need to be developed and background data need adaptation, high load of work	-	not possible to implement	-	not possible to implement	-	not possible to implement	+	already implemented

C Appendix: Air pollutants

Tab. C.1 Detailed comparison of the air pollutant indicators according to the "True & Fair View" requirements (Schwegler et al. 2011); +: good performance; -: bad performance; +/-; both good and bad performance

Characteristics	NEEDS		Eco-indicator 99		IMPACT2002+		ReCiPe endpoint		ReCiPe midpoint		TRACI	
Environmental relevance	+	Secondary particulate matter included but carcinogenic substances and diesel soot not included	+	Secondary particulate matter, carcinogenic substances and diesel soot included	+	secondary particulate matter and carcinogenic substances included, diesel soot excluded	+	secondary particulate matter, human toxic substances included, diesel soot excluded	+	Only primary and secondary particulate matter included	+	only primary and secondary particulate matter inclduded
Focus on the overall picture	+	covers relevant air pollutants (particulate matter)	+	covers all relevant air pollutants including carcinogenics	+	covers all relevant air pollutants	+	covers all relevant air pollutants	+	covers relevant air pollutants (particulate matter)	+	covers relevant air pollutants (particulate matter)
Reliability	+	The method is scientifically sound and has a high reliability and credibility. However, the indicator is based external costs which does not reflect a particular cause-effect chain and units cannot be compared with other methods using DALYs	+	The method is scientifically sound and has a high reliability and credibility. However, the indicator is outdated and should be replaced with the ReCiPe method	+	The method is scientifically sound and has a high reliability and credibility.	+	The method is scientifically sound and has a high reliability and credibility.	+	The method is scientifically sound and has a high reliability and credibility.	+	The method is scientifically sound and has a high reliability and credibility.
Transparency	+/-	The method is of medium difficulty to understand and the calculations are transparent and published.	+/-	The method is of difficult to understand and the calculations are transparent and published.	+/-	The method is of difficult to understand and the calculations are transparent and published.	+/-	The method is of difficult to understand and the calculations are transparent and published.	+	The method is of medium difficulty to understand and the calculations are transparent and published.	+	The method is of medium difficulty to understand and the calculations are transparent and published.
Comprehensibility (communicability)	+/-	The communicability of the indicator is good, since it is only one number and the impacts as external costs are easy to understand.	+/-	The communicability of the indicator is good, since it is only one number but the impacts in DALYs are difficult to understand.	+/-	The communicability of the indicator is good, since it is only one number but the impacts in DALYs are difficult to understand.	+/-	The communicability of the indicator is good, since it is only one number but the impacts in DALYs are difficult to understand.	+/-	The communicability of the indicator is good, since it is only one number but the virtuality of PM10 are difficult to understand.	+/-	The communicability of the indicator is good, since it is only one number but the virtuality of PM2.5 are difficult to understand.
Coherence + Comparability	+/-	Comparability of the times series is only given if there is no change in the database and impact factors.	+/-	Comparability of the times series is only given if there is no change in the database and impact factors.	+/-	Comparability of the times series is only given if there is no change in the database and impact factors.	+/-	Comparability of the times series is only given if there is no change in the database and impact factors.	+/-	Comparability of the times series is only given if there is no change in the database and impact factors.	+/-	Comparability of the times series is only given if there is no change in the database and impact factors.
Availability of information: Data availability and quality	+	Data sources not analysed	+	data sources not analysed	+	data sources not analysed	+	data sources not analysed	+	data sources not analysed	+	data sources not analysed
Timeliness (up-to-date information)	+	published 2009	-	outdated published in the year 2000	+	published in 2005	+	published in 2008	+	published in 2008	+	published in 2011
Ease of the implementation	+	already implemented in current LCA software	+	already implemented in current LCA software	+	already implemented in current LCA software	+	already implemented in current LCA software	+	already implemented in current LCA software	+	already implemented in current LCA software

D Appendix: Nitrogen

Tab. D.1 Detailed comparison of the eutrophication indicators according to the “True & Fair View” requirements (Schwegler et al. 2011); +: good performance; -: bad performance; +/-; both good and bad performance

Characteristics	Phosphorus extraction		Nitrogen fixation		Marine eutrophication	
Environmental relevance	+/-	Good for agricultural products, to a lesser extent for broader set of products and materials	+/-	Good for a broad set of products and materials and medium for agricultural products only	+	Marine eutrophication is valid impact pathw ay for eutrophication due to nitrogen emissions
Focus on the overall picture	+/-	phosphorus extraction is able to cover eutrophying impacts of agriculture but not for a broad set of products and materials	+/-	nitrogen fixation is able to cover eutrophying impacts of a broad set of products, but correlation for agricultural products is lacking	+	covers relevant eutrophying substances and fate modeling using CARMEN
Reliability	+/-	Phosphorus extraction calculated based on extraction of phosphorus resources derived from life cycle inventories	+/-	Nitrogen calculated based on industrial nitrogen fixation derived from life cycle inventories	+	The method is scientifically sound and has a high reliability and credibility.
Transparency	+	data based on ecoinvent 2.2 data, is reliable and transparent	+	data based on ecoinvent 2.2 data, is reliable and transparent	+	The method is of medium difficulty to understand and the calculations are transparent and published.
Comprehensibility (communicability)	+	Kilograms of phosphorus resources depleted	+	kg of ammonia synthesised	+/-	The communicability of the indicator is good, since it is only one number but the virtuality of nitrogen equivalents are difficult to understand.
Coherence + Comparability	+	comparability of the time series is given since it is a physical unit but LCI data base is suspect to change	+	comparability of the time series is given since it is a physical unit but LCI data base is suspect to change	+/-	Comparability of the times series is only given if there is no change in the database and impact factors.
Availability of information: Data availability and quality	+	based on ecoinvent 2.2 data, available and good quality	+	based on ecoinvent 2.2 data, available and good quality	+	data sources not analysed
Timeliness (up-to-date information)	+	ecoinvent database updated in 2010	+	ecoinvent database updated in 2010	+	published in 2008
Ease of the implementation	+	already implemented in current LCA softw are	+	already implemented in current LCA softw are	+	already implemented in current LCA softw are

E Appendix: Material use

Tab. E.1 Detailed comparison of the material use indicators according to the “True & Fair View” requirements (Schwegler et al. 2011); +: good performance; -: bad performance; +/-; both good and bad performance

Characteristics	DMC		RMC		TMC		EMC	
Environmental relevance	-	based on w eight, gravel has the highest contribution, only small contribution of non-ferrous metals	+/-	good for metals, chemicals, plastics, energy carriers and biomass, bad for minerals	+/-	good for metals, chemicals, plastics, energy carriers and biomass, bad for minerals	+	eleven major environmental impacts covered
Focus on the overall picture	-	The method uses a single indicator to quantify the direct material consumption, the type of the material is differentiated but aggregated based on w eigth	+/-	Method uses a single indicator to quantify the material demand including used extraction but excluding unused extraction like tailings	+/-	The method uses a single indicator to quantify the direct material consumption, the material is aggregated based on w eigth. Used and unused extractions are included.	+	Method uses a single indicator to quanitfy a broad range of environmental impacts w ithout w eighting of the different impact categories
Reliability	+	The method is easy to understand and the calculations are transparent and published.	+	based on hybrid IO-LCA method for the calculation of RMC, RME of imports (RMEIM), and RME of exports (RMEEX). This	+	The method is easy to understand and the calculations are transparent and published.	+	The method is scientifically sound and has a high reliability and credibility. How ever, the indicator is based on eleven different impacts w hich are aggregated
Transparency	+	Disaggregated flow s are on several levels beyond the main categories of the DMC/DMI are published and accessible.	-	Calculation of the raw material equivalents is published and accessible but difficult to understand	-	Only limited disaggregation of materials flow s in the main categories of the TMC/TMR are published and accessible.	+/-	Calculation of the raw material equivalents is published and accessible but of medium difficulty to understand
Comprehensibility (communicability)	+	The communicability of the indicator is good, since it is only one number and describes a physical unit.	+	The communicability of the indicator is good, since it is only one number but the virtuality of an equivalent is difficult to understand	+	The communicability of the indicator is good, since it is only one number and describes a physical unit.	+/-	The communicability of the indicator is good, since it is only one number but result as a sum of eleven normalised impact categories is difficult to understand
Coherence + Comparability	+	Comparability of the times series is given since there is no change in the factors.	+/-	Comparability of the times series is given if there is no change in the factors (characterisation or normalisation)	+/-	Comparability of the times series is given if there is no change in the factors.	+/-	Comparability of the times series is given if there is no change in the factors (characterisation or normalisation)
Availability of information: Data availability and quality	+	no special data needed for the calcualtion of the characterisation factors	+/-	data on indirect material demand needed	+/-	data on indirect material demand and unused extraction needed	+	based on w ell established major impact cateogories
Timeliness (up-to-date information)	+	available for 2010	+	available for 2010	+	available for 2010	+	available for 2010
Ease of the implementation	+	total sum of consumed materials.	+/-	quantification of cumulative (life cycle based) used resource consumption needed	+/-	quantification of cumulative (life cycle based) unused resource consumption needed	+	assessment of cumulative (life cycle based) resource extraction and emissions. Standard life cycle thinking approach.