Supplementary material

Future greenhouse gas emissions from metal production: gaps and opportunities towards climate goals

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Parameters for material flow analysis

Tables S1–S6 show parameters used for material flow analysis. Here, δ, θ, λ, ξ, γ, and ω are the primary production yield, secondary production yield, manufacturing yield, new scrap recovery rate, old scrap collection rate, and in-use dissipation rate, respectively.

Table S1 Parameters for aluminum.

	Market share	Lifetime distribution (Weibull)		δ	θ	λ	ξ	γ	ω
		Average lifetime (years)	Shape parameter						
Construction	24%	55	3.5	88%	97%	59%	95%	70%	0%
Transportation	28%	20	3.5	88%	97%	59%	95%	75%	0%
Machinery	8%	25	3.5	88%	97%	59%	95%	45%	0%
Electronics	12%	40	3.5	88%	97%	59%	95%	50%	0%
Containers	15%	1	3.5	88%	97%	59%	95%	60%	0%
Products	7%	15	3.5	88%	97%	59%	95%	20%	0%
Other	6%	12	3.5	88%	97%	59%	95%	20%	0%
Ref.	1, 2	2, 3	4	5	5	5	5	2	1

Table S2 Parameters for copper.

	Market share	Lifetime distribution (Weibull)		δ	θ	λ	ξ	γ	ω
		Average lifetime (years)	Shape parameter						
Construction	35%	28	4.0	83%	100%	82%	92%	69%	1%
Infrastructure	26%	50	2.5	83%	100%	82%	92%	60%	2%
Electronics	22%	15	1.75	83%	100%	82%	92%	60%	0%
Transportation	11%	14	1.5	83%	100%	82%	92%	60%	1%
On-site waste	6%	1	1.5	83%	100%	82%	92%	72%	0%
Ref.	3	3	6	5	5	5	5	3	3

Table S3 Parameters for iron.

	Market share	Lifetime distribution (Weibull)		δ	θ	λ	ξ	γ	ω
		Average lifetime (years)	Shape parameter						
Construction	48%	60	3.5	87%	94%	89%	100%	82%	1%
Transportation	13%	13	3.5	87%	94%	89%	100%	87%	1%
Machinery	31%	15	3.5	87%	94%	89%	100%	82%	1%
Products	8%	25	3.5	87%	94%	89%	100%	58%	1%
Ref.	3	7	7	5	5	5	5	8	5

Table S4 Parameters for lead.

	Market share	Lifetime distribution (Weibull)		δ	θ	λ	ξ	γ	ω
		Average lifetime (years)	Shape parameter						
Battery (transportation)	50%	4	3.5	89%	100%	94%	80%	75%	0%
Battery (industrial)	25%	10	3.5	89%	100%	94%	80%	75%	0%
Cable sheathing	1%	16	2.7	89%	100%	94%	80%	30%	0%
Alloys	9%	14	1.8	89%	100%	94%	80%	50%	0%
Chemicals	9%	1	1.8	89%	100%	94%	80%	0%	0%
Other	6%	14	1.8	89%	100%	94%	80%	0%	0%
Ref.	3	9	9	5	5	5	5	9	1

Table S5 Parameters for nickel.

	Market share	Lifetime distribution (Weibull)		δ	θ	λ	ξ	γ	ω
		Average lifetime (years)	Shape parameter						
Construction	18%	50	3.0	79%	100%	86%	84%	87%	0%
Transportation	17%	17	3.0	79%	100%	86%	84%	74%	0%
Machinery	31%	25	3.0	79%	100%	86%	84%	87%	0%
Electronics	12%	15	3.0	79%	100%	86%	84%	29%	0%
Metal goods	23%	15	3.0	79%	100%	86%	84%	48%	0%
Ref.	3	2, 3	10	5	5	5	5	3	5

Table S6 Parameters for zinc.

	Market share	Lifetime distribution (Weibull)		δ	θ	λ	ξ	γ	ω
		Average lifetime (years)	Shape parameter						
Galvanizing	47%	17	3.5	84%	64%	78%	91%	0%	12%
Zinc-based alloys	16%	19	3.5	84%	64%	78%	91%	19%	0%
Bronze and brass	19%	16	3.5	84%	64%	78%	91%	19%	0%
Other	18%	14	1.81	84%	64%	78%	91%	19%	4%
Ref.	3	3	9	5	5	5	5	3, 9	1

Parameters for SSPs

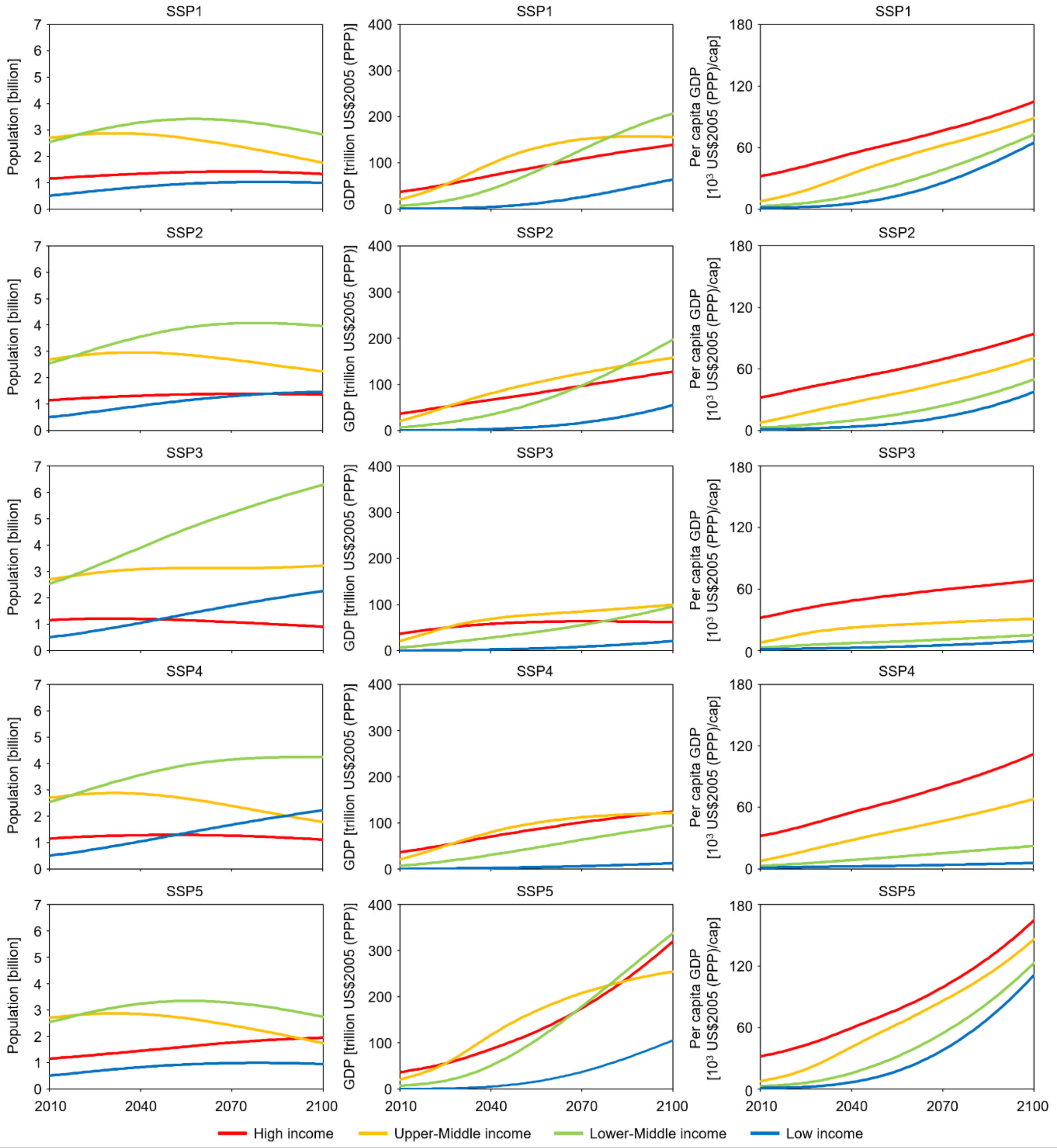

Fig. S1 Population and GDP growth by income level groups for SSPs.

Additional results

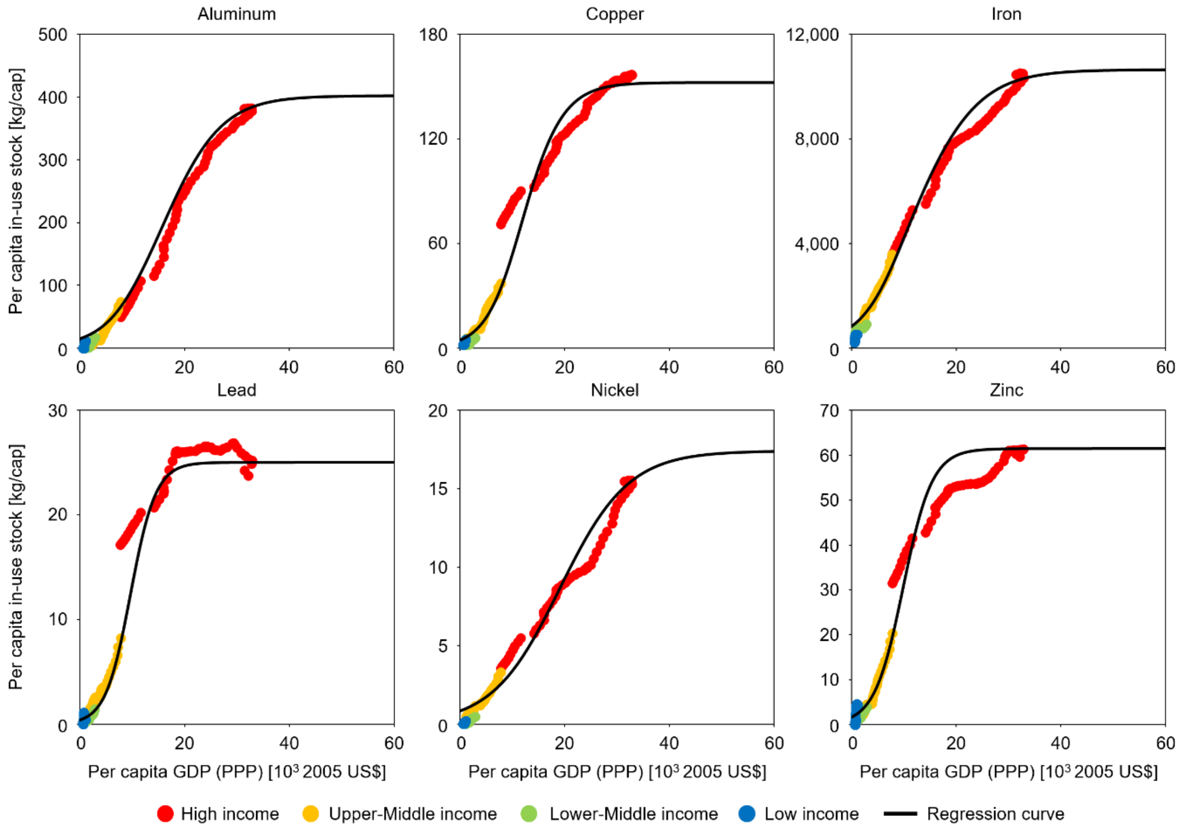

Fig. S2 Historical data (plots) and derived logistic curves for the six metals. Results for all end uses are aggregated.

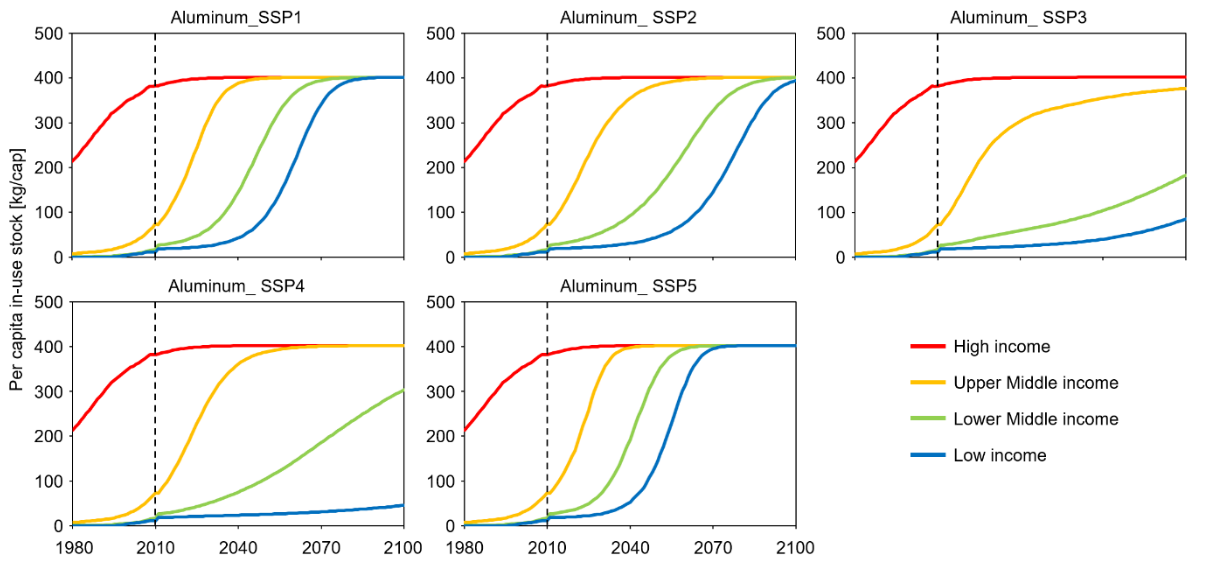

Fig. S3 Per capita in-use aluminum stocks by income level groups.

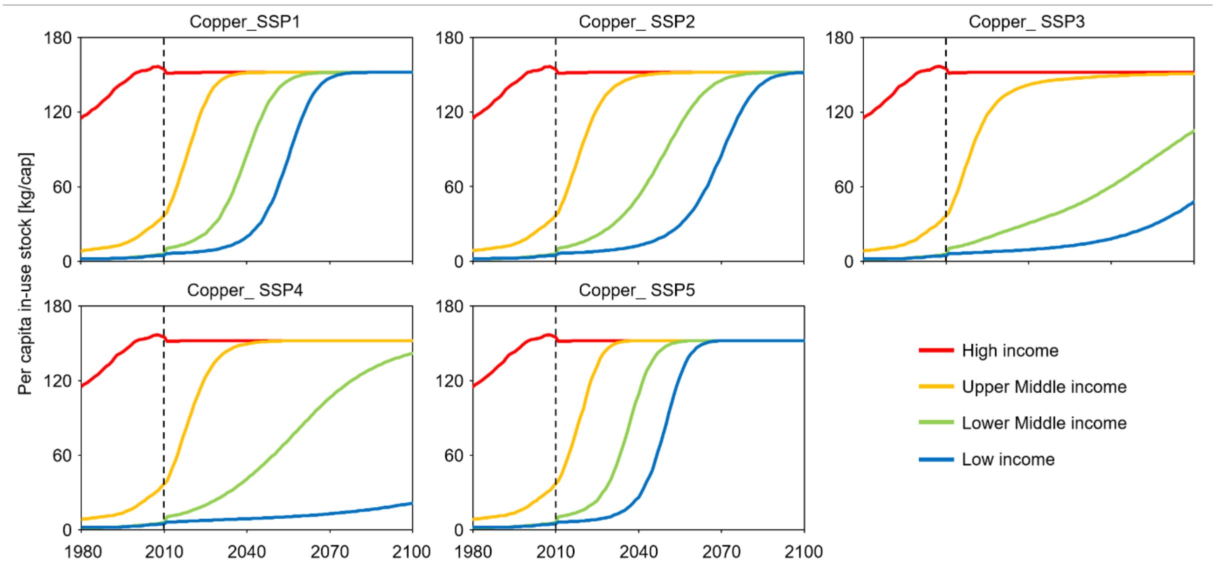

Fig. S4 Per capita in-use copper stocks by income level groups.

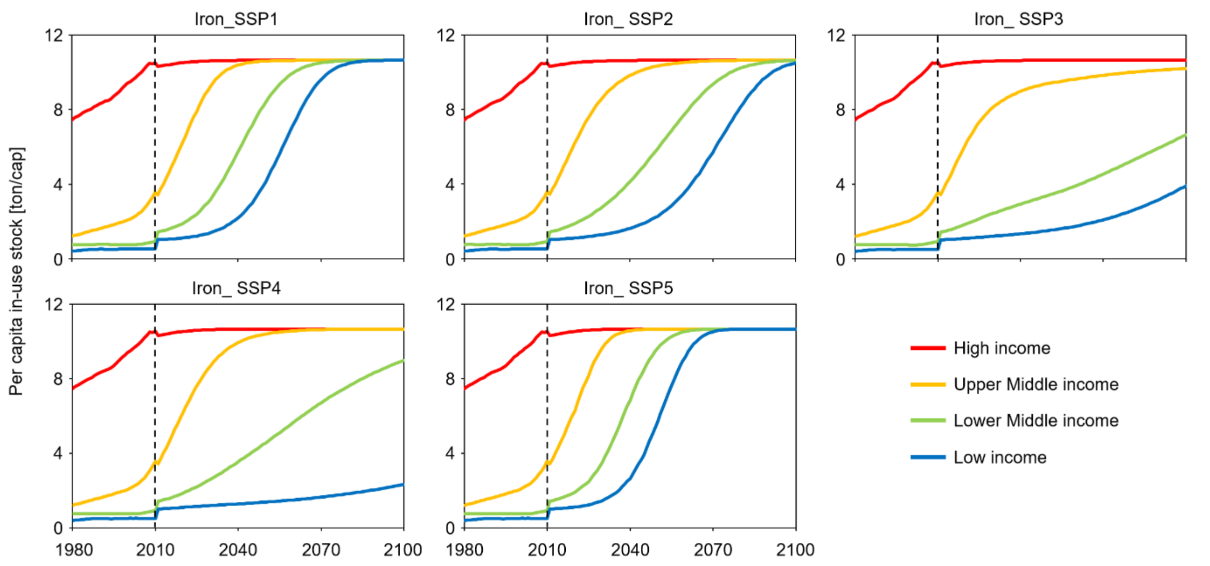

Fig. S5 Per capita in-use iron stocks by income level groups.

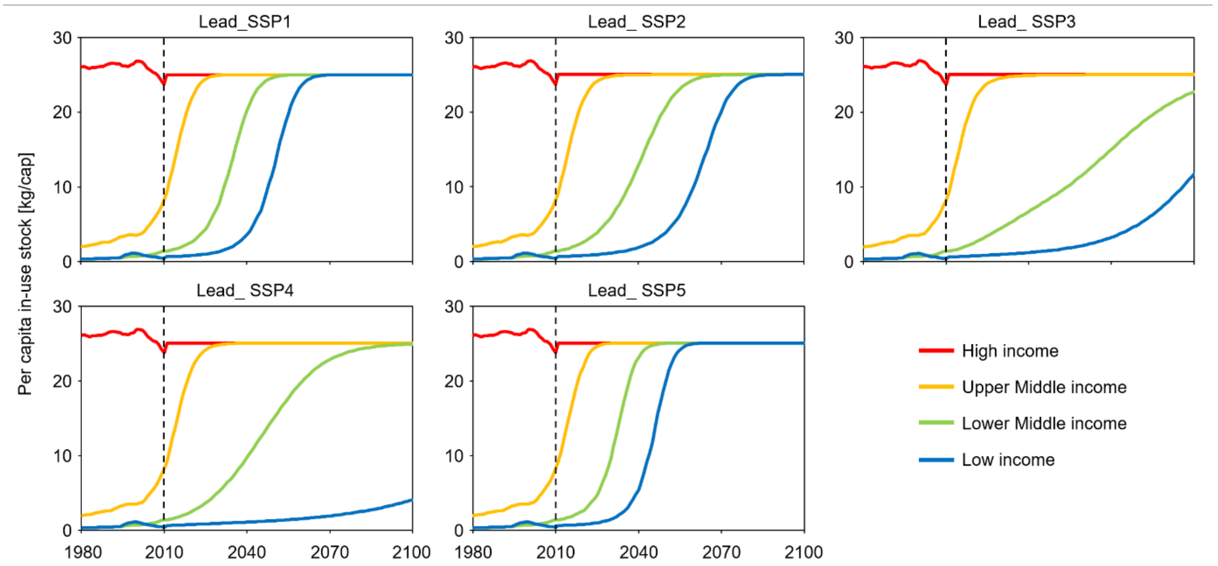

Fig. S6 Per capita in-use lead stocks by income level groups.

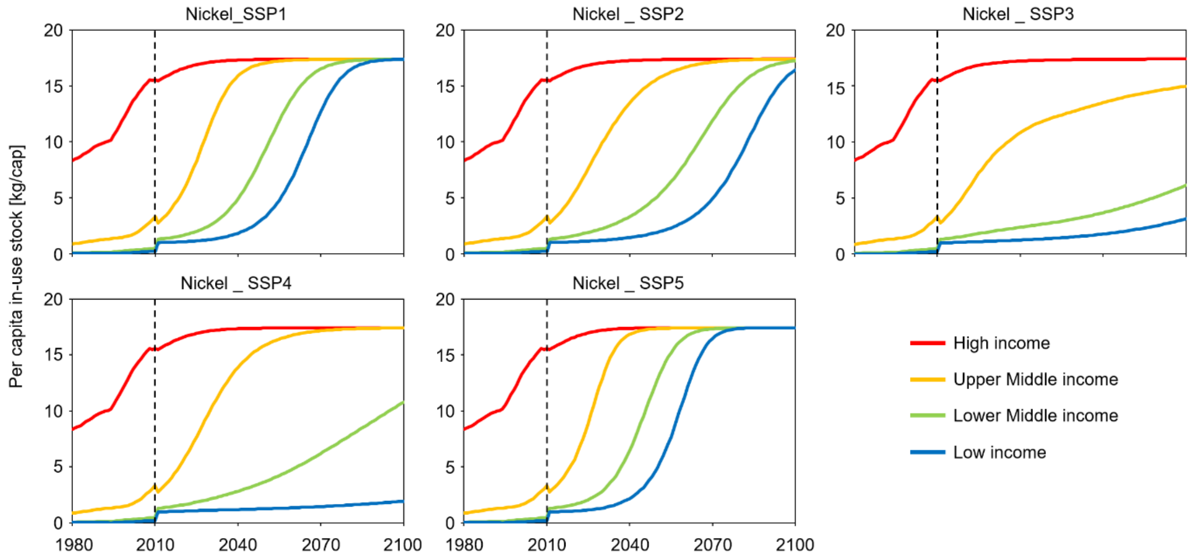

Fig. S7 Per capita in-use nickel stocks by income level groups.

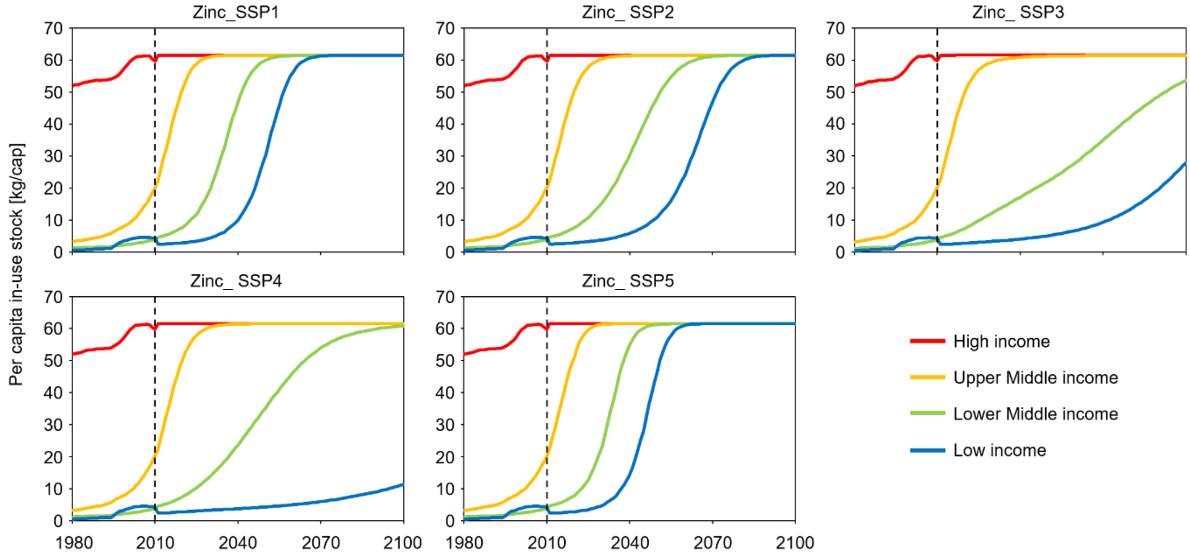

Fig. S8 Per capita in-use zinc stocks by income level groups.

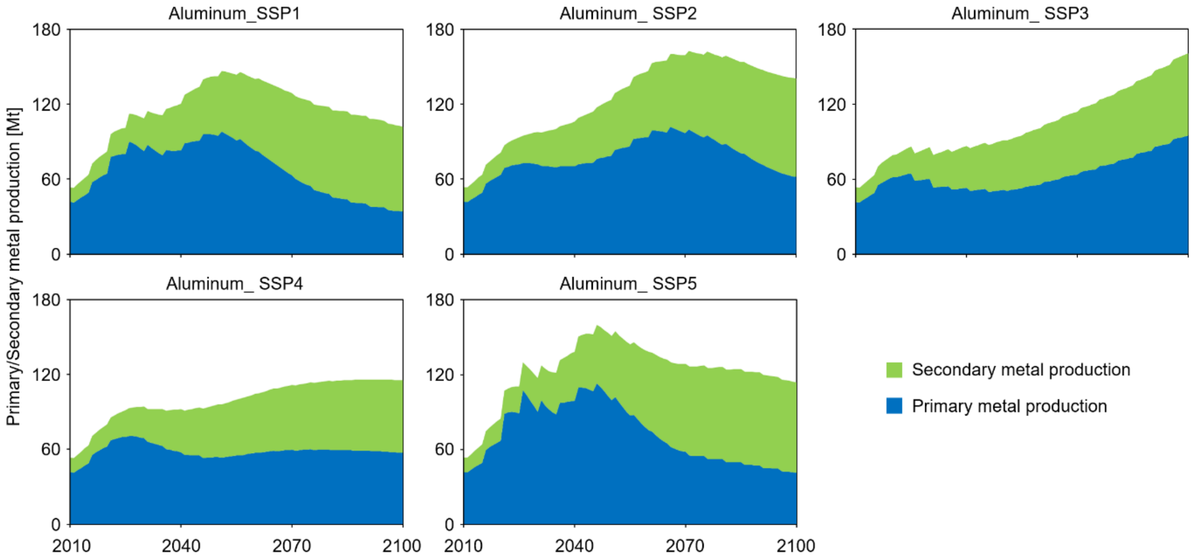

Fig. S9 Primary and secondary production of aluminum for 2010–2100 by SSPs.

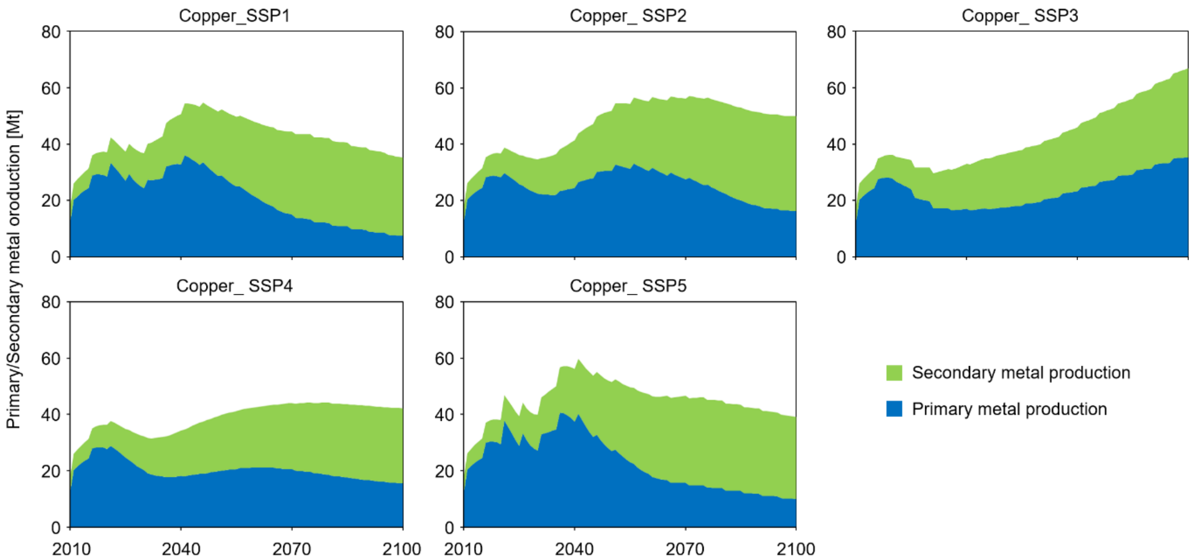

Fig. S10 Primary and secondary production of copper for 2010–2100 by SSPs.

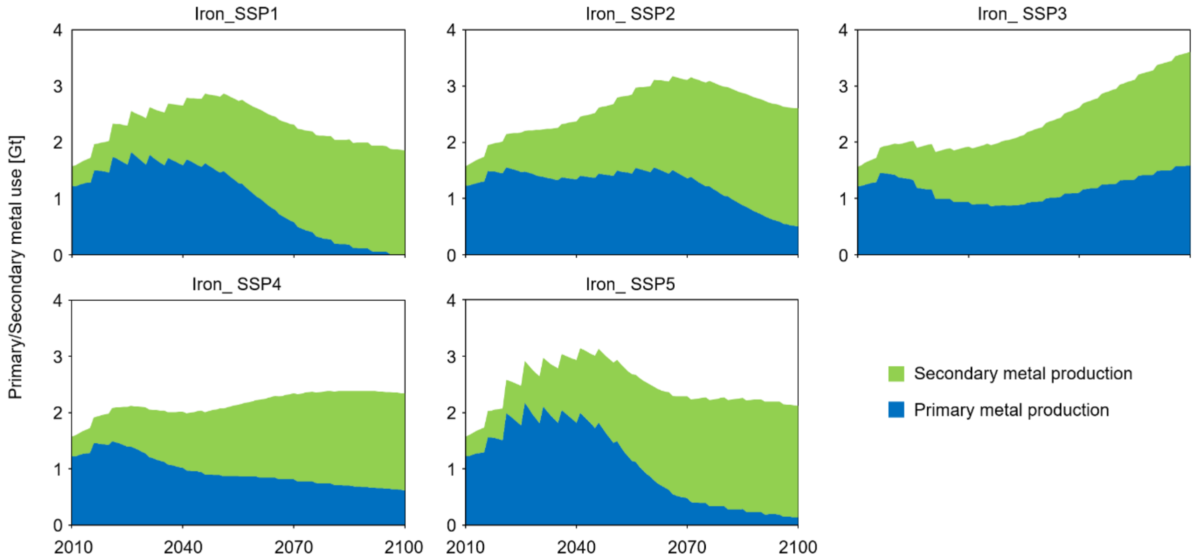

Fig. S11 Primary and secondary production of iron for 2010–2100 by SSPs.

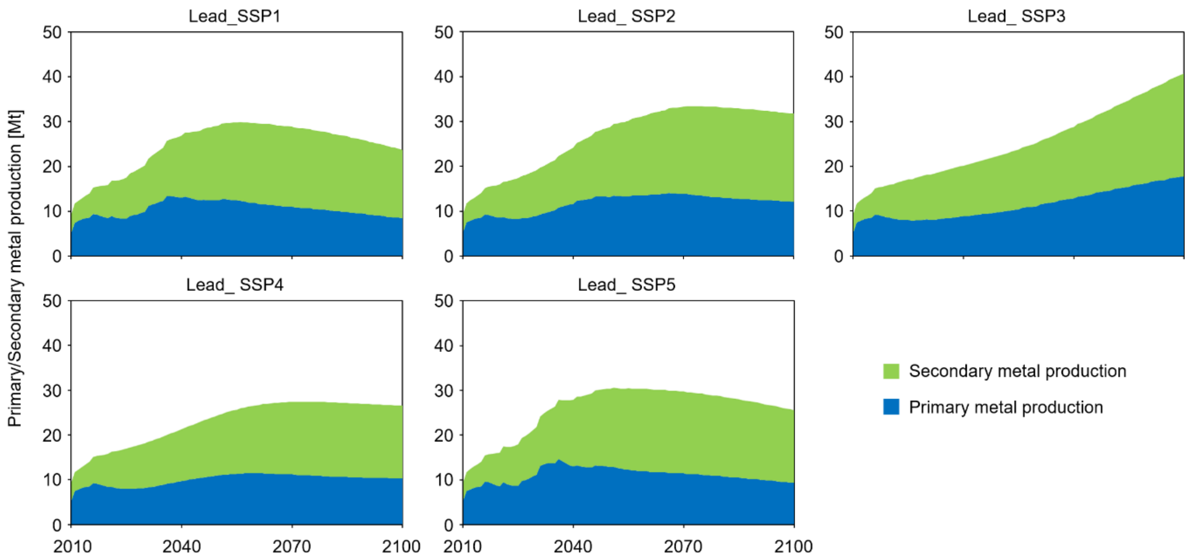

Fig. S12 Primary and secondary production of lead for 2010–2100 by SSPs.

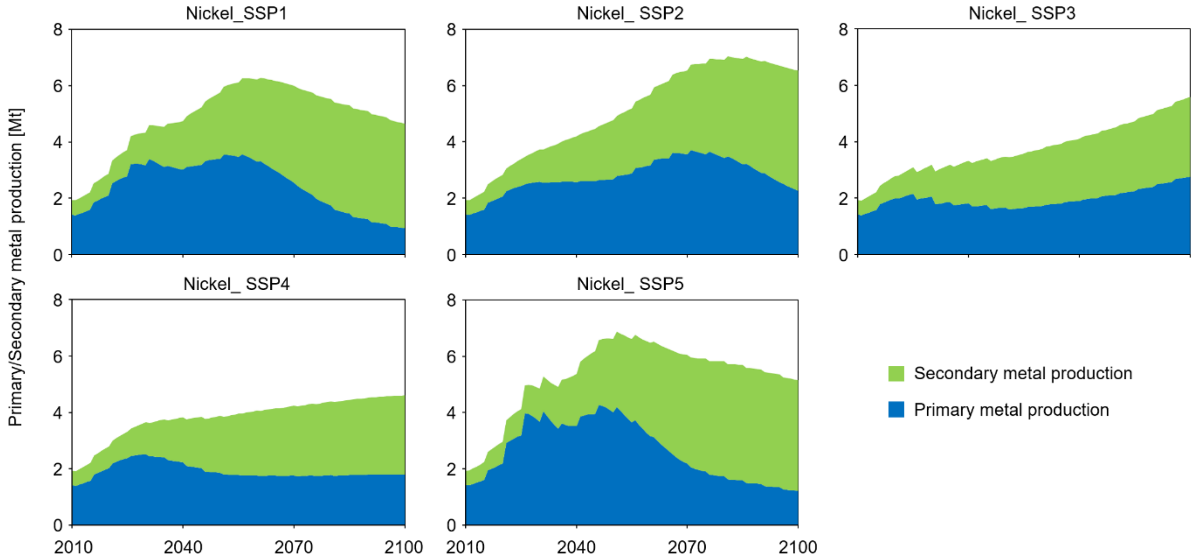

Fig. S13 Primary and secondary production of nickel for 2010–2100 by SSPs.

Fig. S14 Primary and secondary production of zinc for 2010–2100 by SSPs.

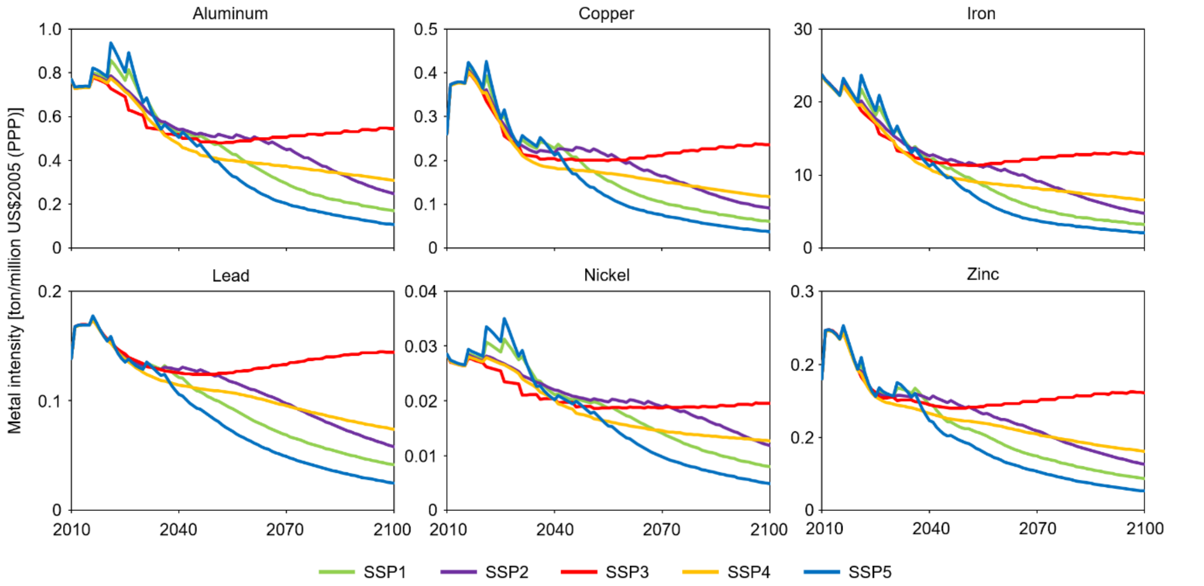

Fig. S15 Metal intensity of the six metals for 2010–2100 by SSPs.

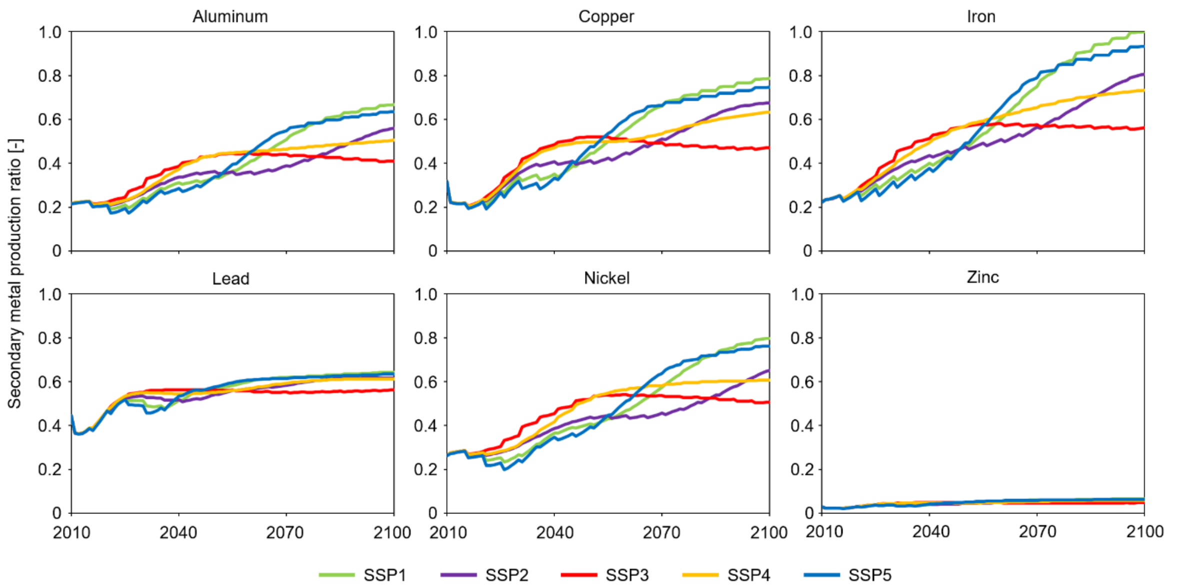

Fig. S16 Secondary metal production ratios of the six metals for 2010–2100 by SSPs.

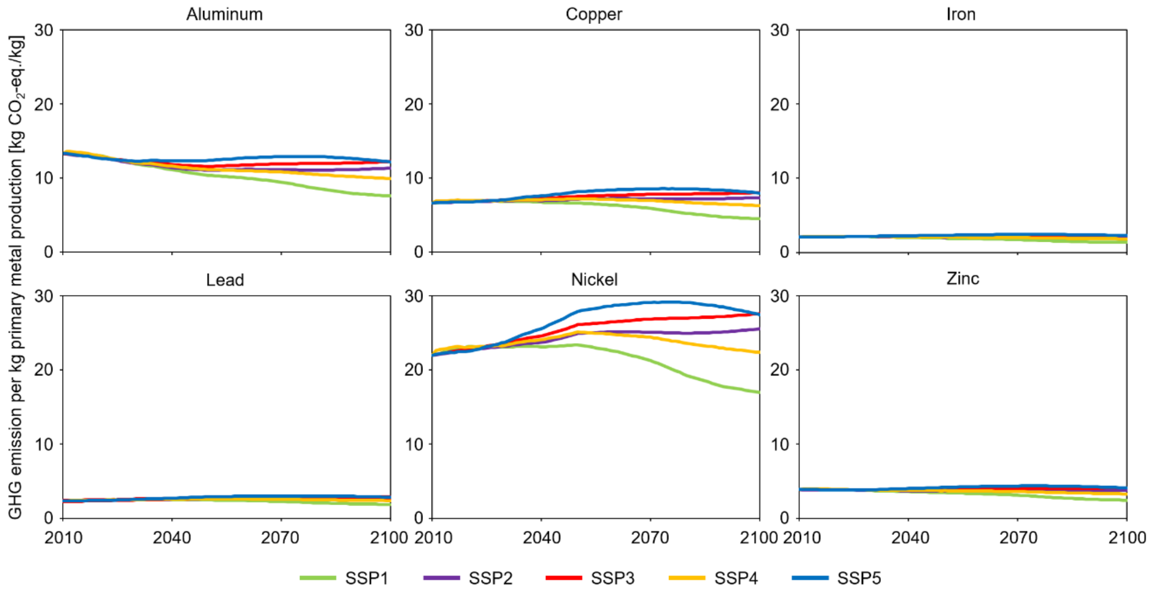

Fig. S17 GHG emissions per kg primary metal production for 2010–2100 by SSPs.

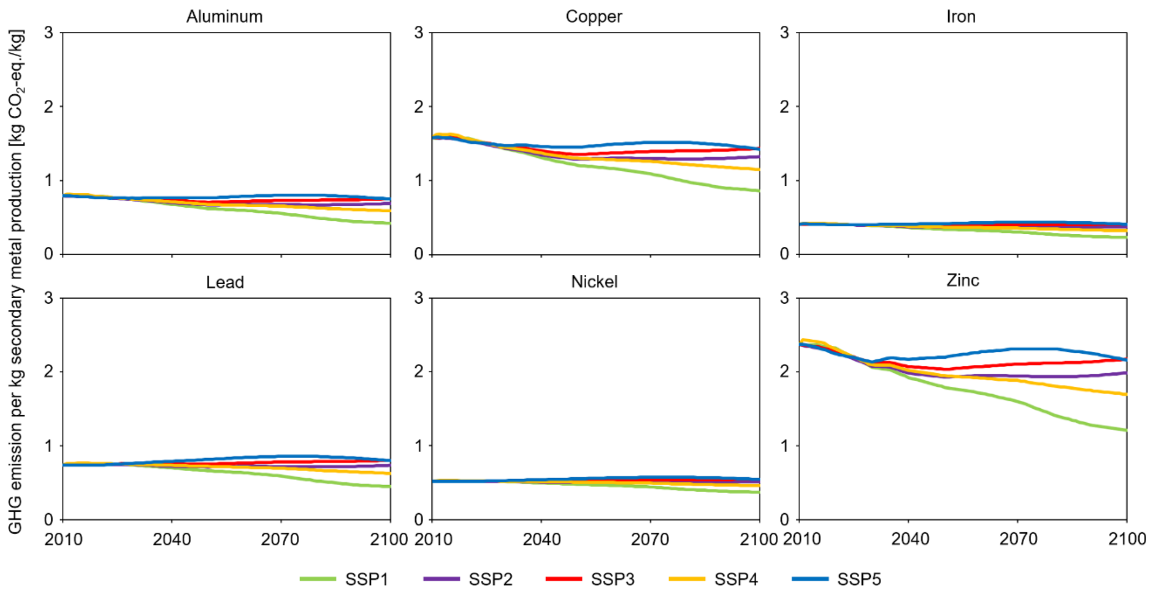

Fig. S18 GHG emissions per kg secondary metal production for 2010–2100 by SSPs.

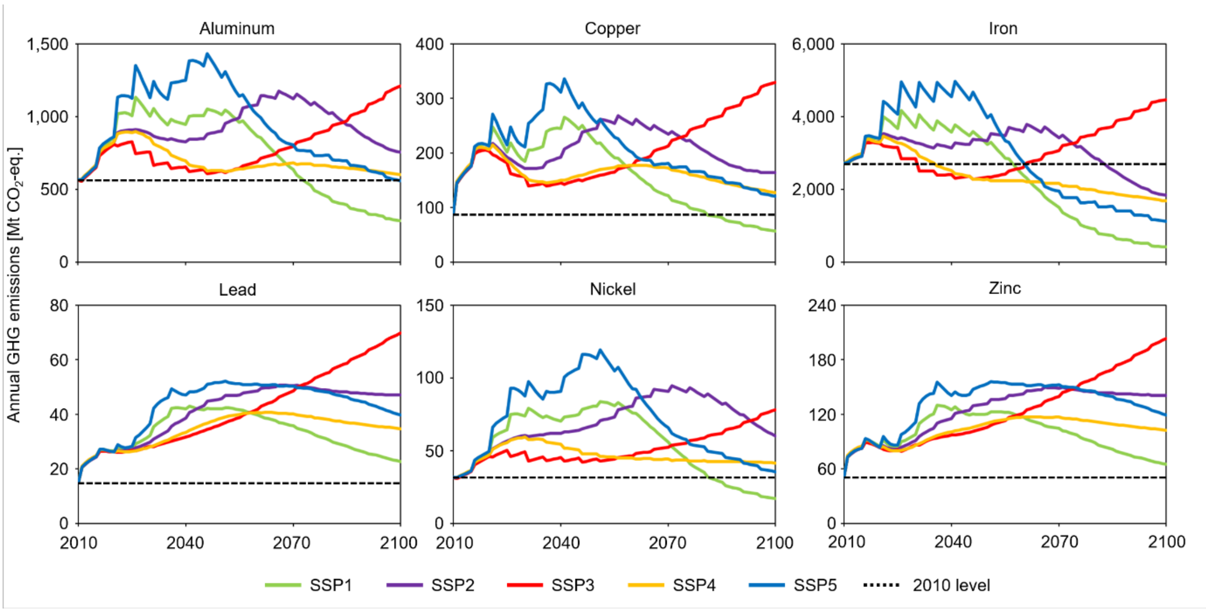

Fig. S19 Annual GHG emissions associated with the production of the six metals for 2010–2100 by SSPs.

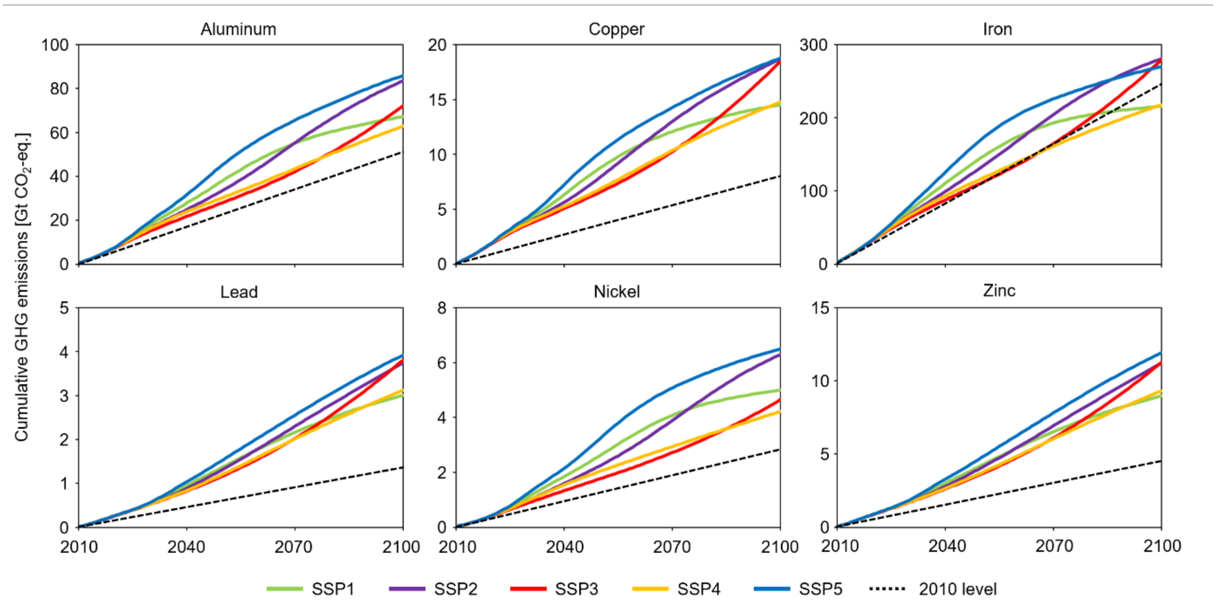

Fig. S20 Cumulative GHG emissions associated with the production of the six metals for 2010–2100 by SSPs. The black dotted line indicates the cumulative GHG emission assuming the constant annual GHG emission level in 2010.

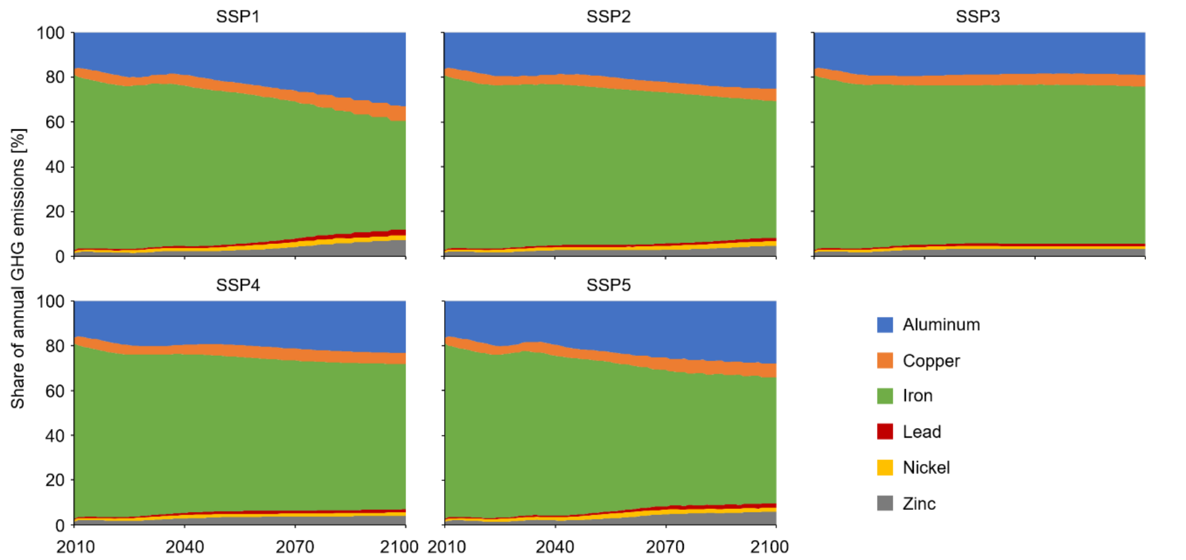

Fig. S21 Share of the annual GHG emissions associated with the production of the six metals for 2010–2100 by SSPs.

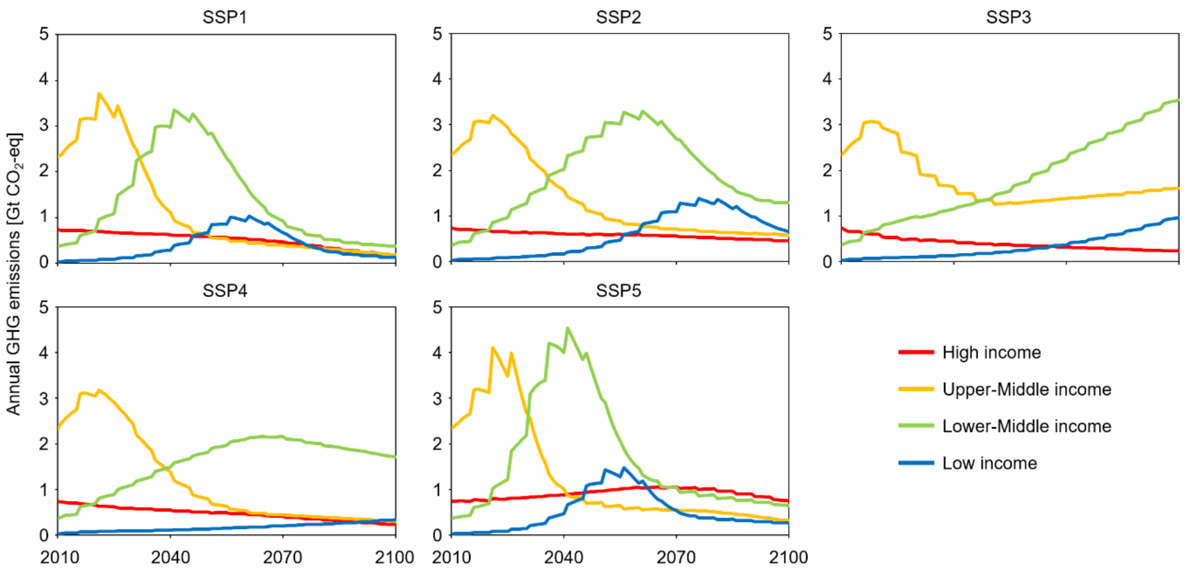

Fig. S22 Annual GHG emissions associated with metal production by income level groups.

Fig. S23 Cumulative GHG emissions associated with metal production by income level groups.

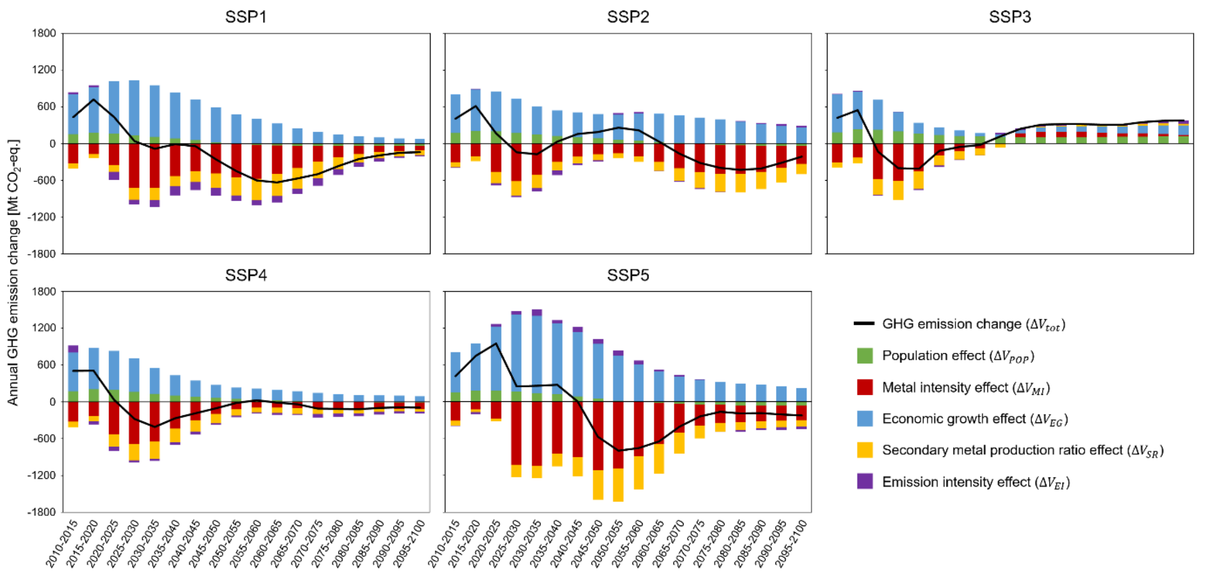

Fig. S24 Decomposition analysis of changes in the annual GHG emissions associated with the metal production every five years from 2010 to 2100. The summation of contributions of the five effects is equal to GHG emission changes.

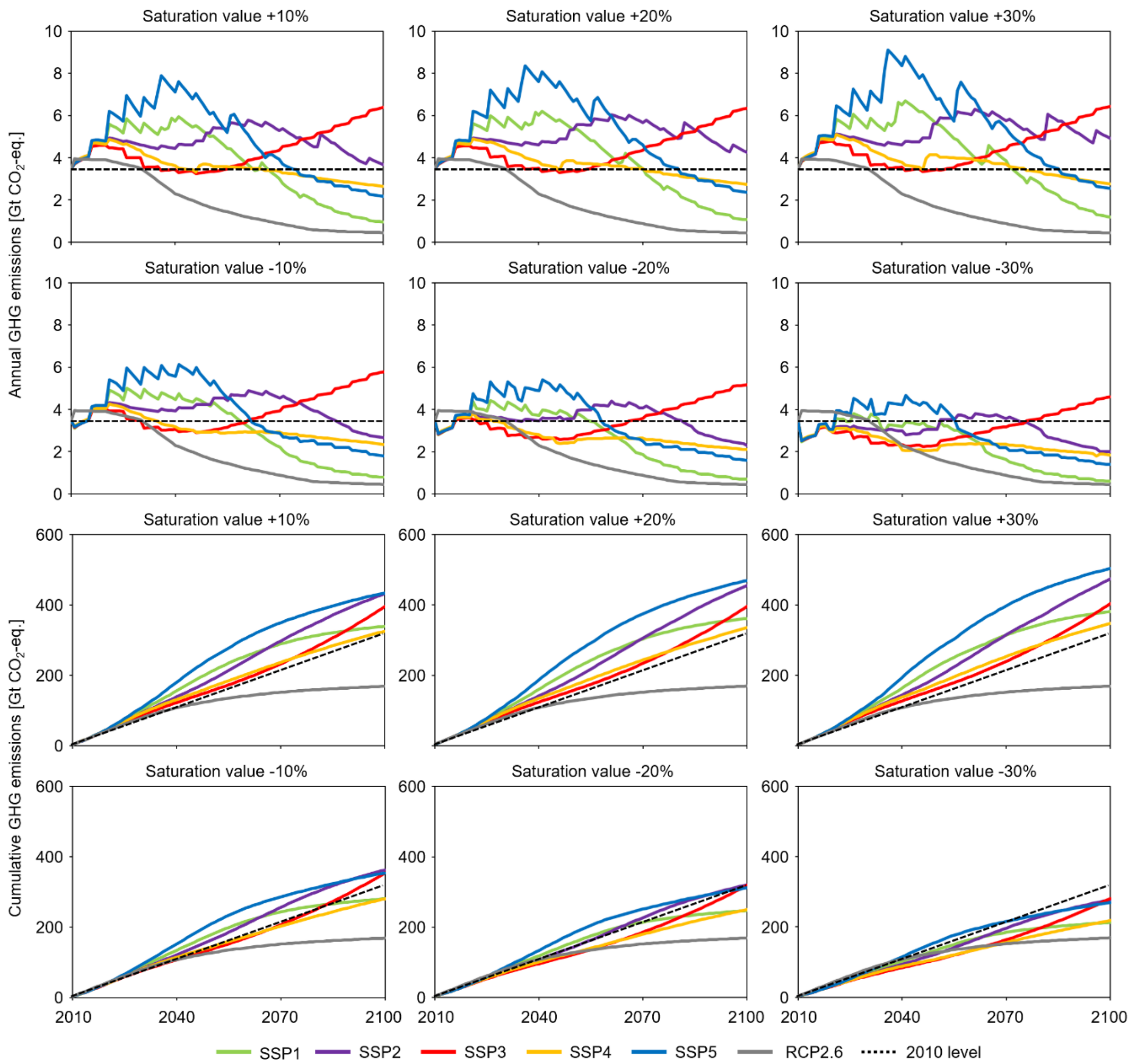

Fig. S25 Annual and cumulative GHG emissions with different saturation values.

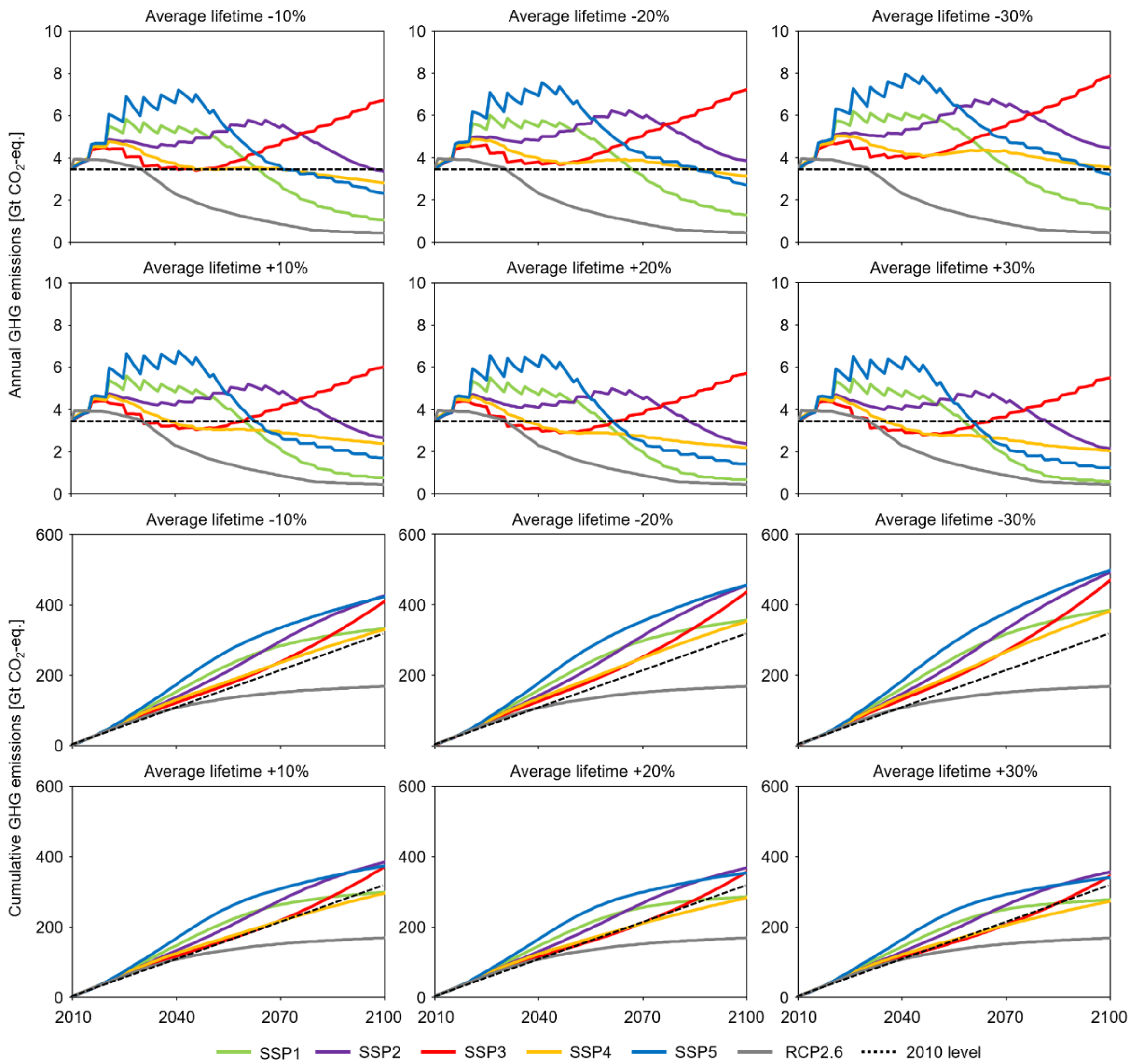

Fig. S26 Annual and cumulative GHG emissions with different average lifetimes.

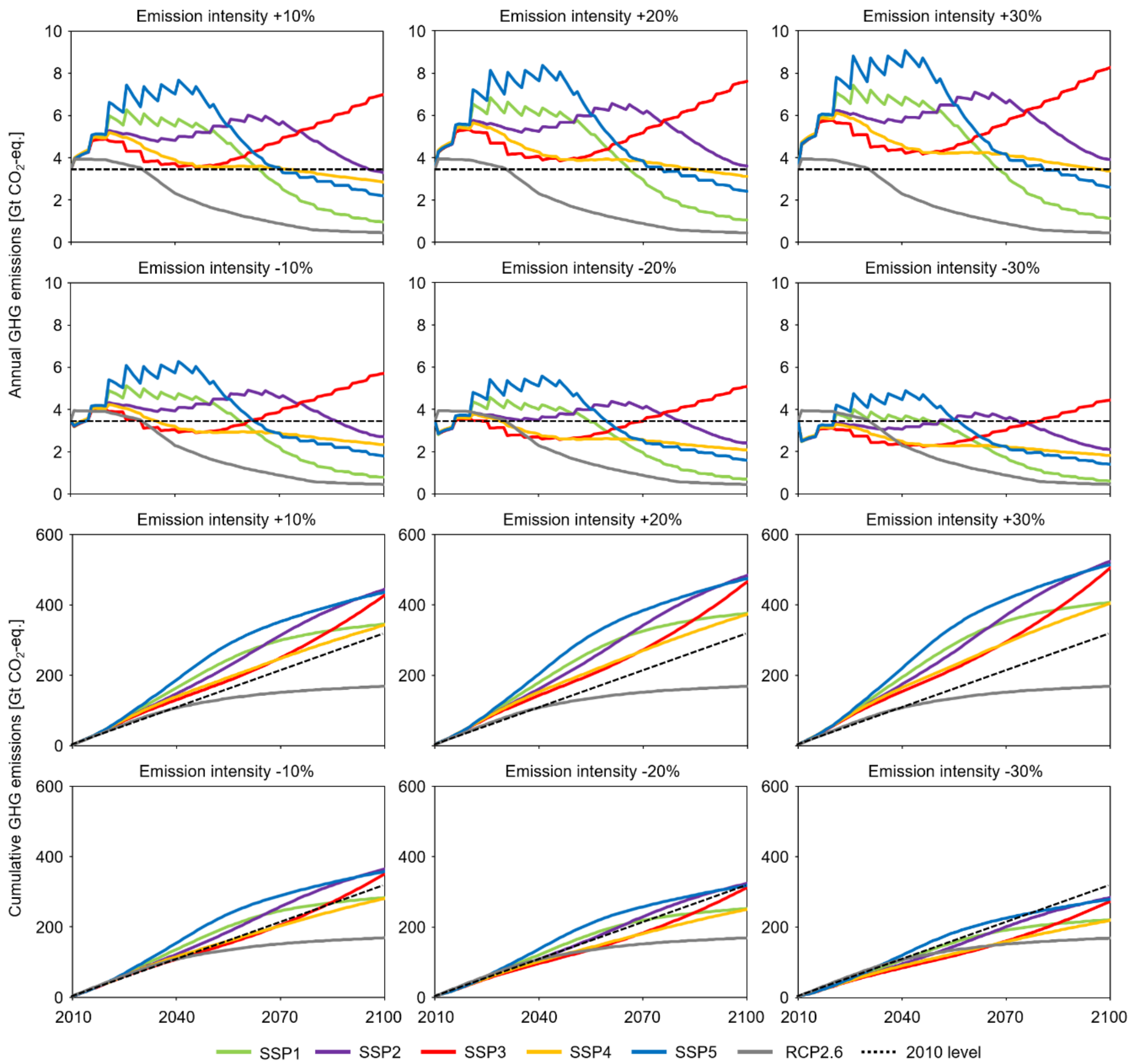

Fig. S27 Annual and cumulative GHG emissions with different emission intensities.

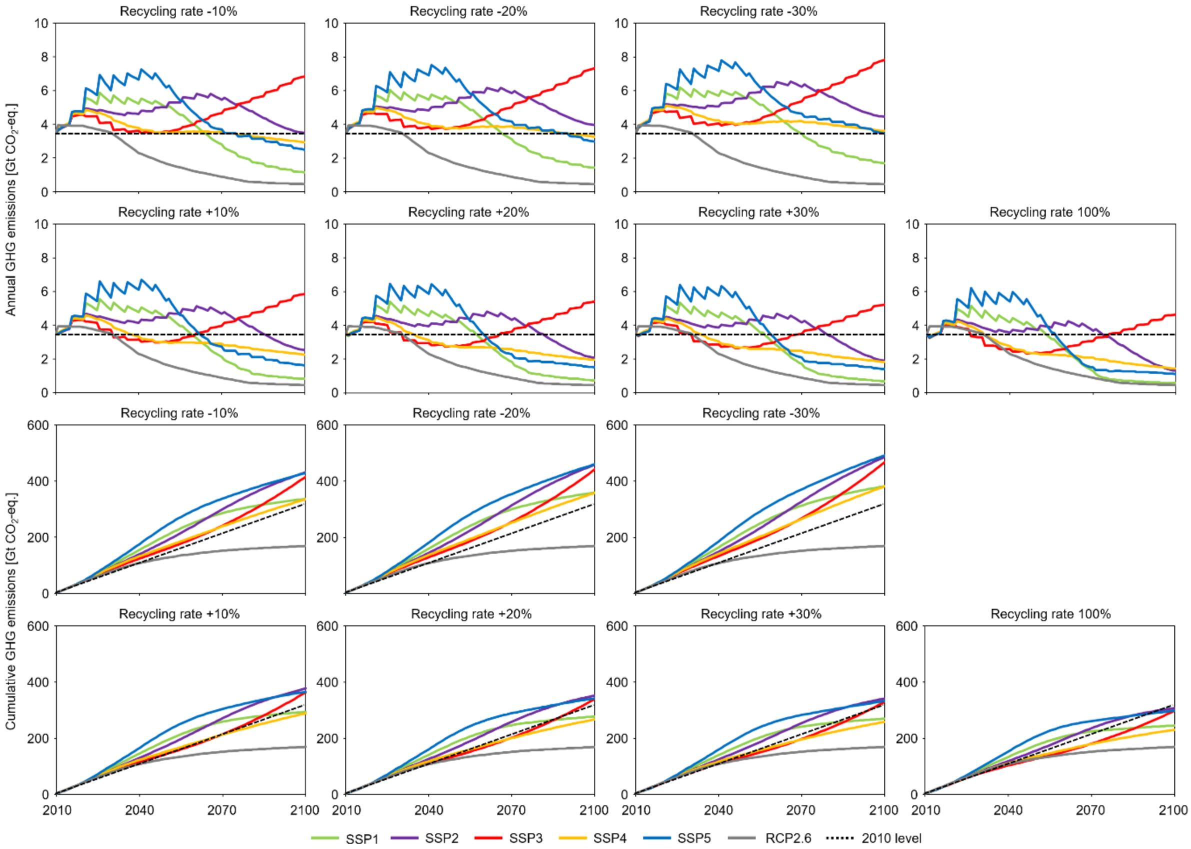

Fig. S28 Annual and cumulative GHG emissions with different recycling rates.

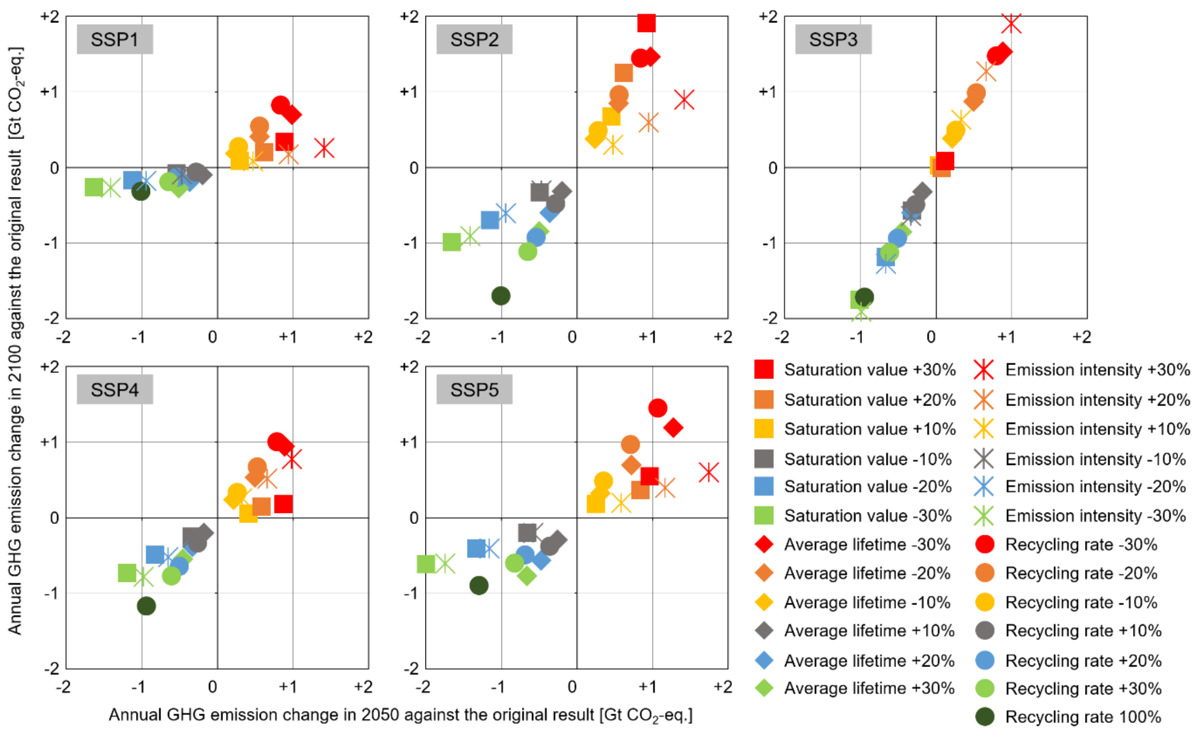

Fig. S29 Annual GHG emission changes in 2050 and 2100 from the original results by varying parameters.

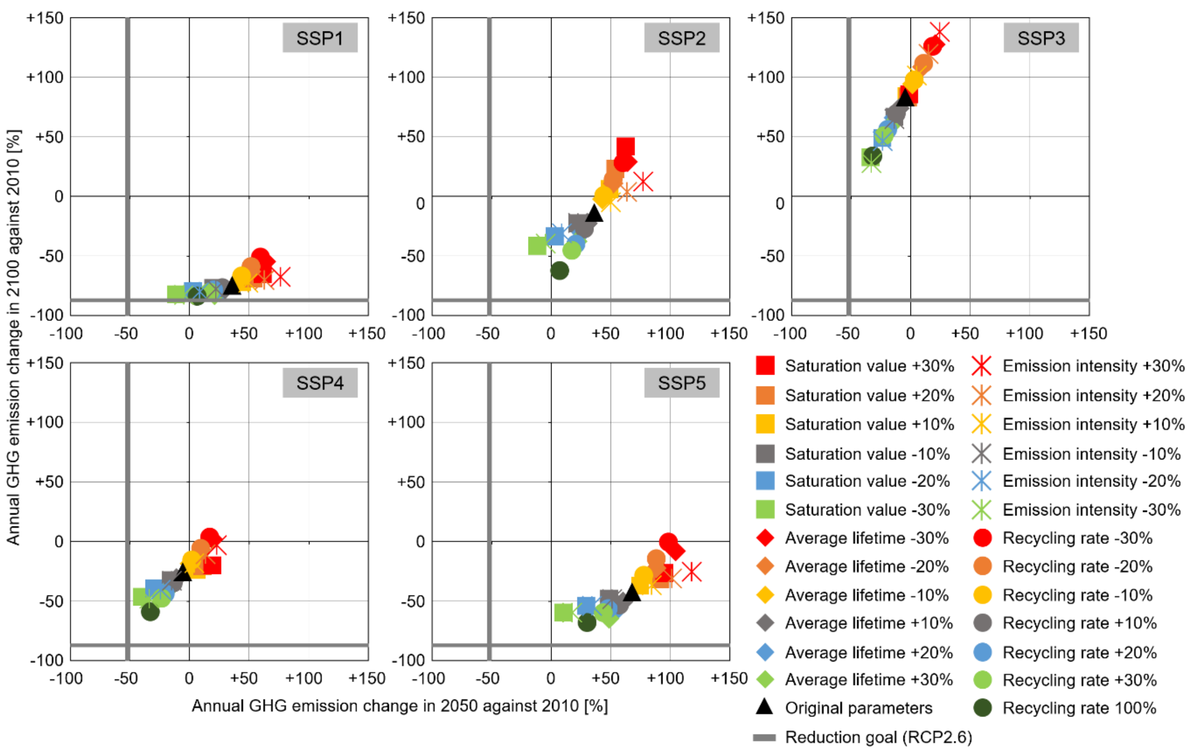

Fig. S30 Annual GHG emission changes compared with 2010 by varying parameters.

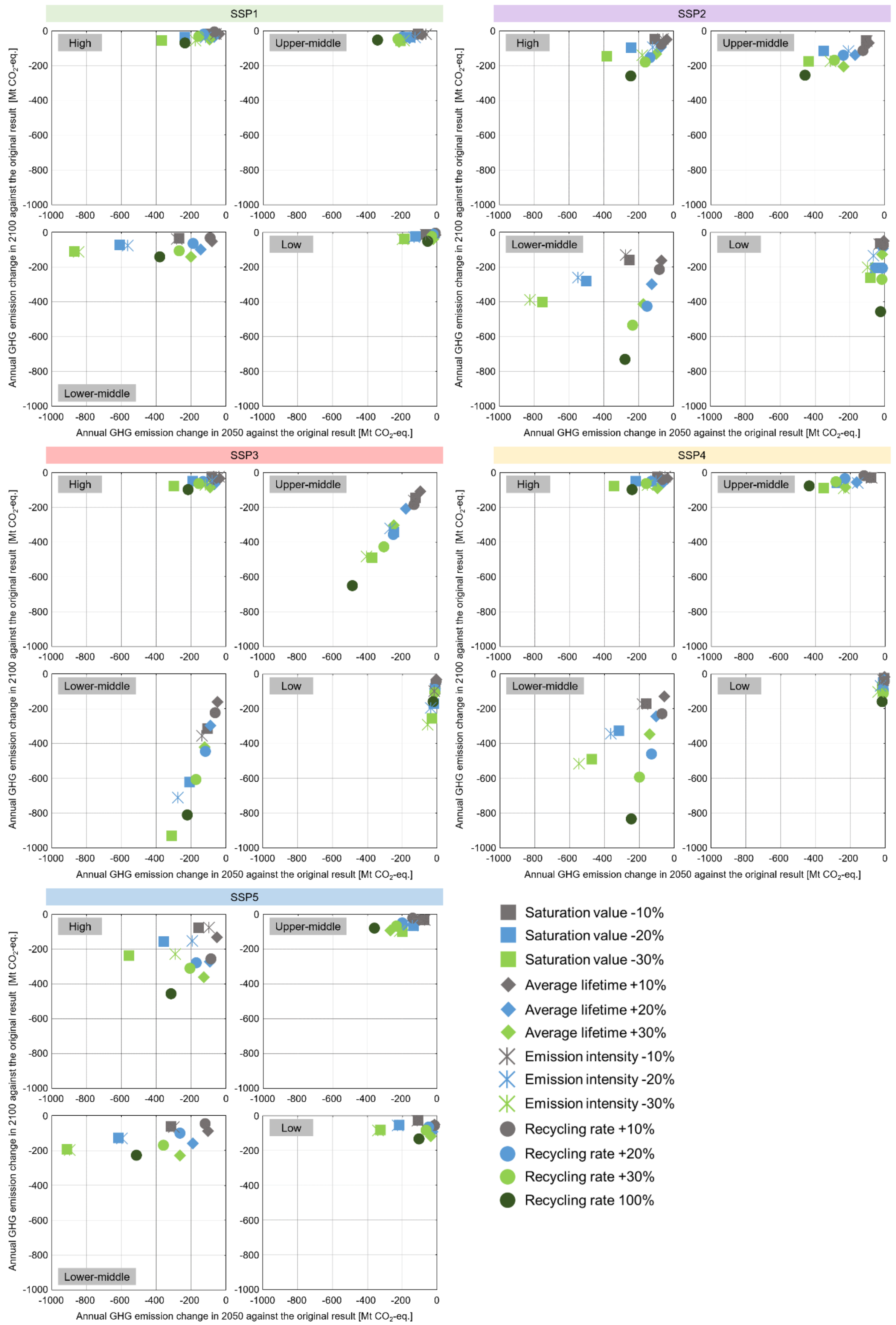

Fig. S31 Annual GHG emission changes from the original results by income level groups.

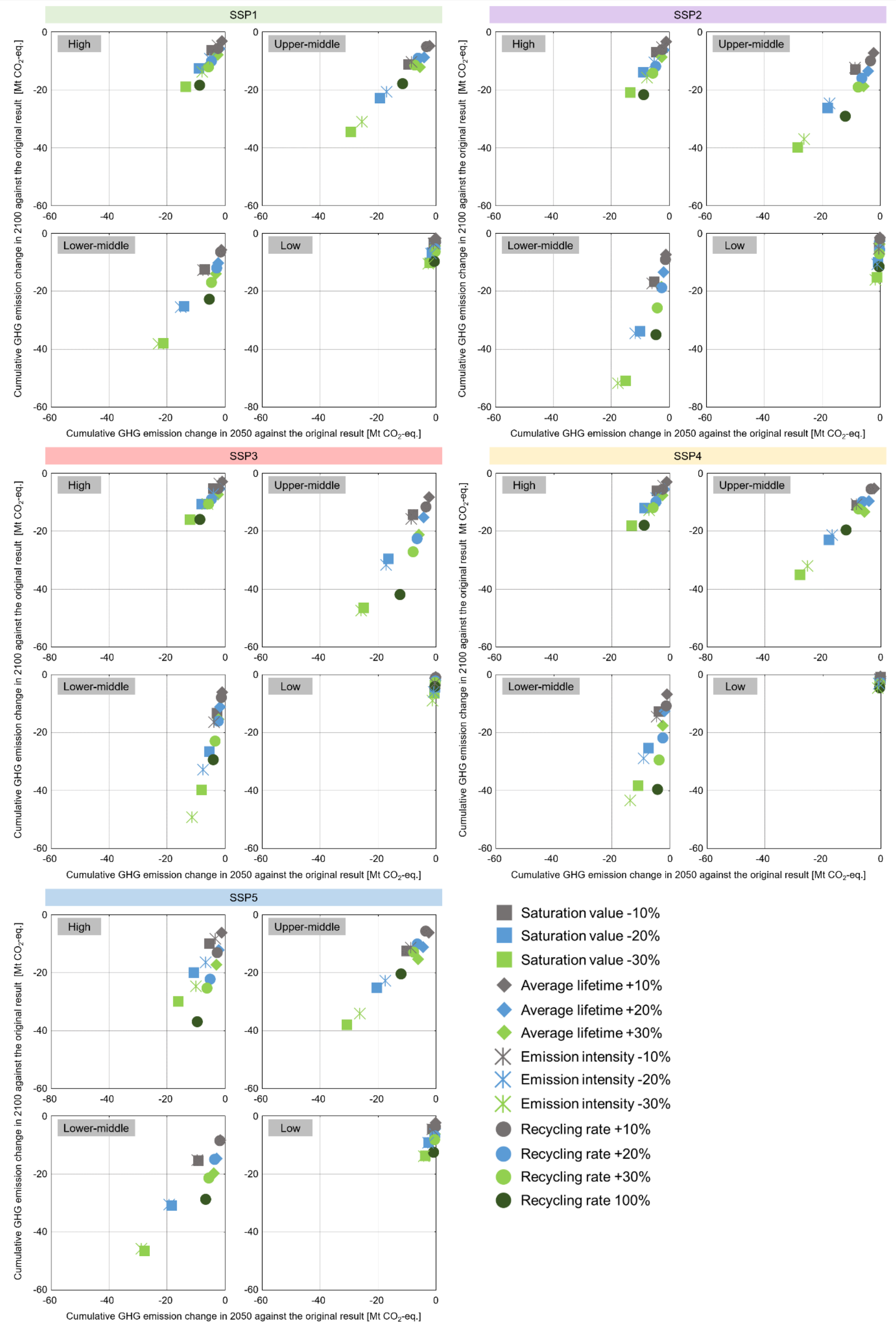

Fig. S32 Cumulative GHG emission changes from the original results by income level groups.

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