Body weight impact of the sugar sweetened beverages tax in Mexican children: a modeling study

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Contents

1 Weight change model

We adapted the Dynamics of Childhood Growth and Obesity model (DCGO) from Hall et al., and Katan et al.,[1, 2] to the Mexican population. Briefly, this physiological weight change model considers the interactions between **fat mass**, $FM := FM(t)$, **fat free mass**, $FFM := FFM(t)$, an **energy intake** function, $I := I(t)$, and an **energy expenditure** function, $E := E(t)$, adjusted by a **body-growth term**, $g(t)$. In this model, **body weight** is given by the sum of **fat mass** and **fat free mass**:

$$BW := BW(t) = FM(t) + FFM(t). \tag{1}$$

In particular, **body weight** (BW) is a function of time t, depends on the individual's characteristics for **sex** (Sex), **initial fat mass** (FM_0), **initial fat free mass** (FFM_0) and **energy intake** ($I(t)$).This is represented as:

$$BW := BW\big(t; \text{Sex}, FM_0, FFM_0, I(t)\big). \tag{2}$$

The components of BW, FM and FFM are determined by a system of ordinary differential equations:

$$\begin{aligned} \hat{\rho}_{FFM} \cdot \frac{dFFM}{dt} &= p \cdot (I - E) + g(t), \\ \rho_{FM} \cdot \frac{dFM}{dt} &= (1-p) \cdot (I - E) - g(t). \end{aligned} \tag{3}$$

where $p = C/(C + FM)$ corresponds to a ratio established by Forbes [1] where $C = 10.4$ $\hat{\rho}_{FFM}/\rho_{FM}$. The parameters ρ_{FM} and $\hat{\rho}_{FFM}$ correspond to the constants $\rho_{FM} = 9.4$ kcal/g ($= 9400$ kcal/kg) and $\hat{\rho}_{FFM} = (4.3 \cdot FFM + 837)$ kcal/kg, where FFM represents the reference fat free mass (kg) data.
For system (3), to account for the **growth term** ($g(t)$) we used the function:

$$g(t) = A \cdot e^{-(t-t_A)/\tau_A} + B \cdot e^{-(t-t_B)^2/2\tau_B^2} + D \cdot e^{-(t-t_D)^2/2\tau_D^2}, \tag{4}$$

where the specific parameters for males and females are shown in Table 1.[1, 2].

Table 1: **Parameters for the growth function g as established in (4) from [1, 2].**

Parameter	Males	Females	Scale
A	3.2	2.3	kcal/day
B	9.6	8.4	kcal/day
D	10.1	1.1	kcal/day
τ_A	2.5	1	years
τ_B	1	0.9	years
τ_D	1.5	0.7	years
t_A	4.7	4.5	years
t_B	12.5	11.7	years
t_D	15	16.2	years

The **Energy expenditure rate** (E) in (3) is given by:

$$E = K + \gamma_{FFM} FFM + \gamma_{FM} FM + \beta \Delta I + \delta \cdot BW + \eta_{FFM} \cdot \frac{dFFM}{dt} + \eta_{FM} \cdot \frac{dFM}{dt}, \quad (5)$$

where K represents an energy expenditure constant dependent on the indivudal's gender but irrespective of age ($K = 800$ kcal/d for males; $K = 700$ kcal/d for females); $\beta = 0.24$ stands for the adaptation of energy expenditure when energy intake is perturbed ΔI; $\eta_{FM} = 180$ kcal/kg and $\eta_{FFM} = 230$ kcal/kg account for "biochemical efficiencies associated to fat and protein synthesis"[1].

The function for **physical activity** (δ) in (5) is given by:

$$\delta(t) = \delta_{min} + \frac{(\delta_{max} - \delta_{min}) P^h}{t^h + P^h}. \quad (6)$$

The minimum physical activity for all ages and genders is represented by the constant $\delta_{min} = 10$ kcal/kg/d. The constant for maximum physical activity is gender specific and given by $\delta_{max} = 19$ kcal/kg/d for males and $\delta_{max} = 17$ kcal/kg/d for females.

The parameter $P = 12$ years represents the point of maximum physical activity whilst the constant $h = 10$ represents the rate of decline as a function of age.

The **perturbation of energy intake** ΔI in (5) represents the shift away from the energy intake associated with normal growth. Within this work, we have assumed an energy intake rate $I(t)$ equal to the reference energy intake rate $I_{ref}(t)$ described in (7). I_{ref} represents the **reference energy intake** for normal growth:

$$\begin{aligned} I_{ref}(t) = {} & EB_{ref} + K + (\gamma_{FFM} + \delta) FFM_{ref} + (\gamma_{FM} + \delta) FM_{ref} + \frac{\eta_{FFM}}{\rho_{FFM}} (p \cdot EB_{ref} + g) \\ & + \frac{\eta_{FM}}{\rho_{FM}} \big((1-p) \cdot EB_{ref} - g \big). \end{aligned} \quad (7)$$

Thus the ΔI term in equation 5 equals 0.

The **energy balance of reference** (EB_{ref}) used in equation 7 was adapted from Katan et al.[2] and is given by:

$$EB_{ref}(t) = A_{EB} \cdot e^{-(t - t_A^{EB})/\tau_A^{EB}} + B_{EB} \cdot e^{-(t - t_B^{EB})^2 / 2(\tau_B^{EB})^2} + D_{EB} \cdot e^{-(t - t_D^{EB})^2 / 2(\tau_D^{EB})^2}. \quad (8)$$

The gender specific parameters for this function are shown in Table 2.

Table 2: **Parameters for the energy balance function EB_{ref} as established in** (8) **from Katan et al., [2].**

Parameter	Males	Females
A_{EB}	7.2	16.5
B_{EB}	30	47
D_{EB}	21	41
τ_A^{EB}	15	7
τ_B^{EB}	1.5	1
τ_D^{EB}	2	1.5
t_A^{EB}	5.6	4.8
t_B^{EB}	9.8	9.1
t_D^{EB}	15	13.5

Finally with the combination of the above equations, the closed form expression for the **energy expenditure rate** equation (5) is given by:

$$\mathrm{E} = \frac{K + (\gamma_{FFM} + \delta)FFM + (\gamma_{FM} + \delta)FM + \beta \cdot \Delta I + \left(\frac{\eta_{FFM}}{\hat{\rho}_{FFM}}p + \frac{\eta_{FM}}{\rho_{FM}} \cdot (1-p)\right) \cdot I + g \cdot \left(\frac{\eta_{FFM}}{\hat{\rho}_{FFM}} - \frac{\eta_{FM}}{\rho_{FM}}\right)}{1 + \frac{\eta_{FFM}}{\hat{\rho}_{FFM}}p + \frac{\eta_{FM}}{\rho_{FM}} \cdot (1-p)}. \quad (9)$$

1.1 Initial values of fat mass and fat free mass for the system of ordinary differential equations

We estimated the **initial fat mass** (FM_0) used in the system (3) utilizing the equations presented by Deurenberg et al.[3]:

$$FM_0 = \begin{cases} \frac{1.51 \cdot \mathrm{BMI}_0 - 0.7 \cdot a - 2.2}{100} \cdot BW_0, & \text{if Male} \\ \\ \frac{1.51 \cdot \mathrm{BMI}_0 - 0.7 \cdot a + 1.4}{100} \cdot BW_0, & \text{if Female} \end{cases} \quad (10)$$

where a represents the individual's age in years, BMI_0 the initial body mass index (kg/m^2) and BW_0 the initial body weight.

The **initial fat free mass** (FFM_0), for that same system, is given by the difference between initial fat mass and initial body weight:

$$FFM_0 = BW_0 - FM_0. \quad (11)$$

1.2 Reference body composition data

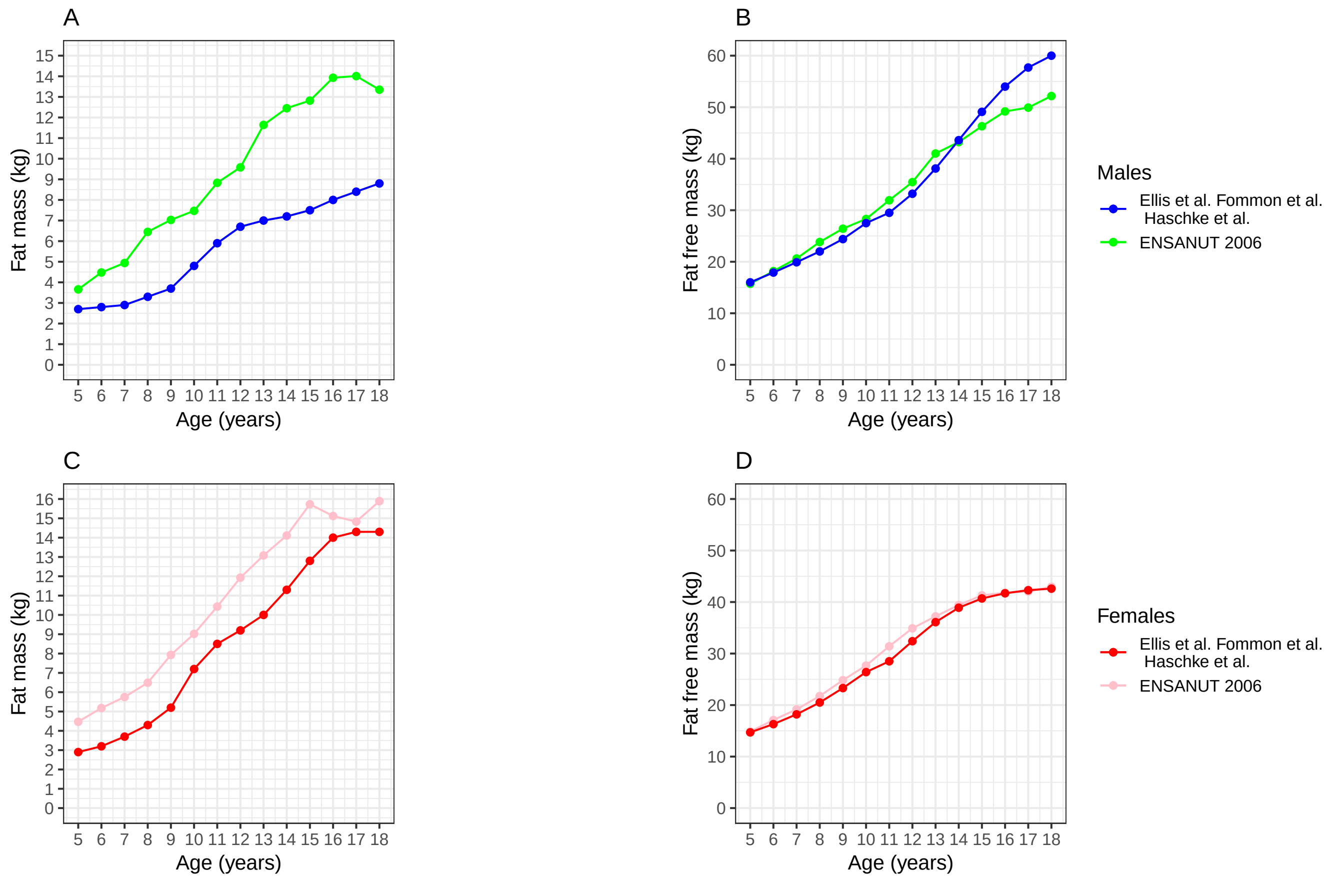
We use data from ENSANUT 2006 to derive reference fat free mass (FFM_{ref}) and reference fat mass (FM_{ref}) values by age and gender for the Mexican population, as shown in Table 3. These were used in the equation (7) for the reference of energy intake term (EB_{ref}) as linear interpolations.

Table 3: **Reference values of fat mass and fat free mass (kg) from ENSANUT 2006** [4]

	Males		**Females**	
Age	Fat Free Mass (kg)	Fat Mass (kg)	Fat Free Mass (kg)	Fat Mass (kg)
5	15.72	3.66	14.86	4.47
6	18.18	4.48	17.09	5.18
7	20.63	4.94	19.16	5.75
8	23.83	6.45	21.75	6.49
9	26.42	7.03	24.83	7.93
10	28.30	7.47	27.67	9.02
11	31.93	8.83	31.41	10.43
12	35.46	9.58	34.90	11.93
13	41.01	11.64	37.22	13.08
14	43.23	12.45	39.41	14.11
15	46.30	12.82	41.30	15.73
16	49.18	13.93	41.80	15.12
17	49.92	14.01	42.05	14.83
18	52.17	13.35	42.96	15.89

Figure 1, shows the difference between the reference FM and FFM data used to calibrate the original DCGO model[5, 6, 7] versus the corresponding values used for the Mexican population. The Mexican data were composed by individuals aged 5 to 18 years from ENSANUT 2006 [4]. We used these reference values to re-calibrate the model and adapt it to the Mexican population.

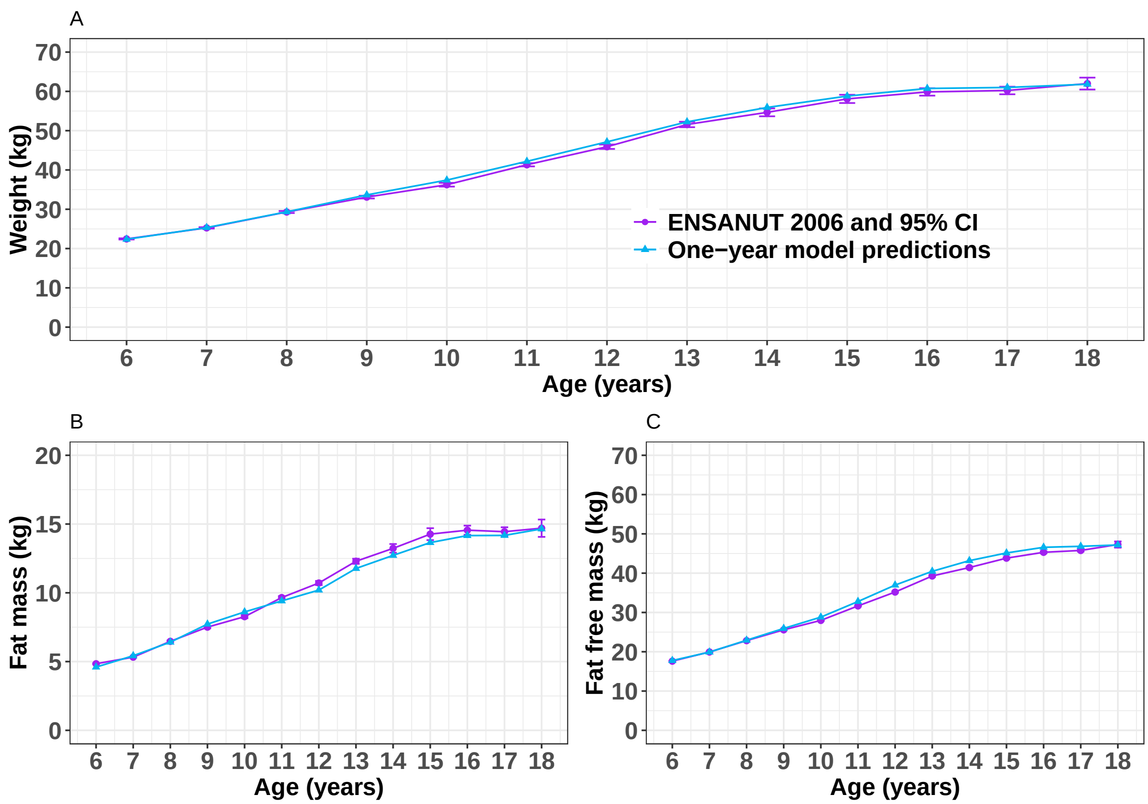
Figure 1: **Comparison between the body composition references [5] [6] [7] used for the DCGO model and [4] for Mexican population, by gender.**



1.3 Model re-calibration and validation

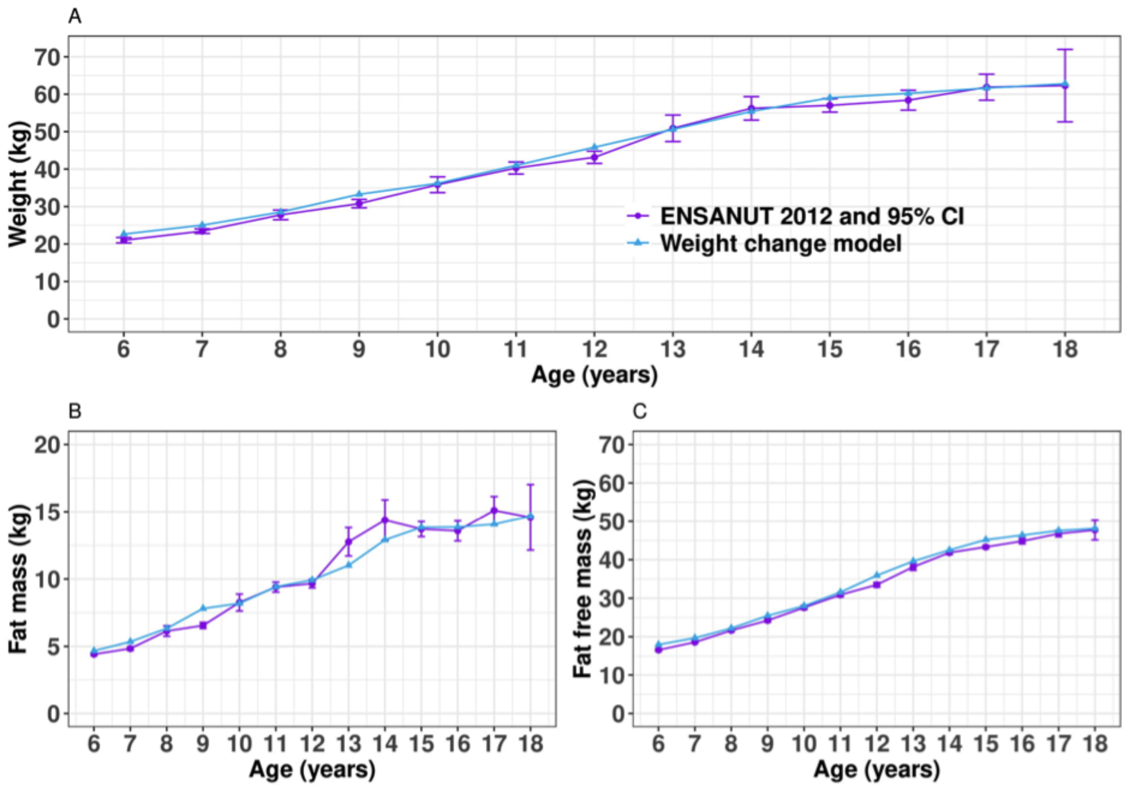
The original DCGO model was re-calibrated to reference body composition data from Mexican children as explained in Section 1.2. A comparison between the one-year simulated weights for children 5-17y (FM and FFM) from ENSANUT 2006 obtained with the DCGO model, and the observed average body weight for children ages 6-18 from ENSANUT 2006, showed an average error of 0.65 kg in weight (Figure 2).

Figure 2: **Comparison of average body composition data between the DCGO model one-year predictions of ENSANUT 2006 [4] children aged 5-17 and ENSANUT 2006 [4] reported average values. Weight (A), fat mass (B) and fat free mass (C).**



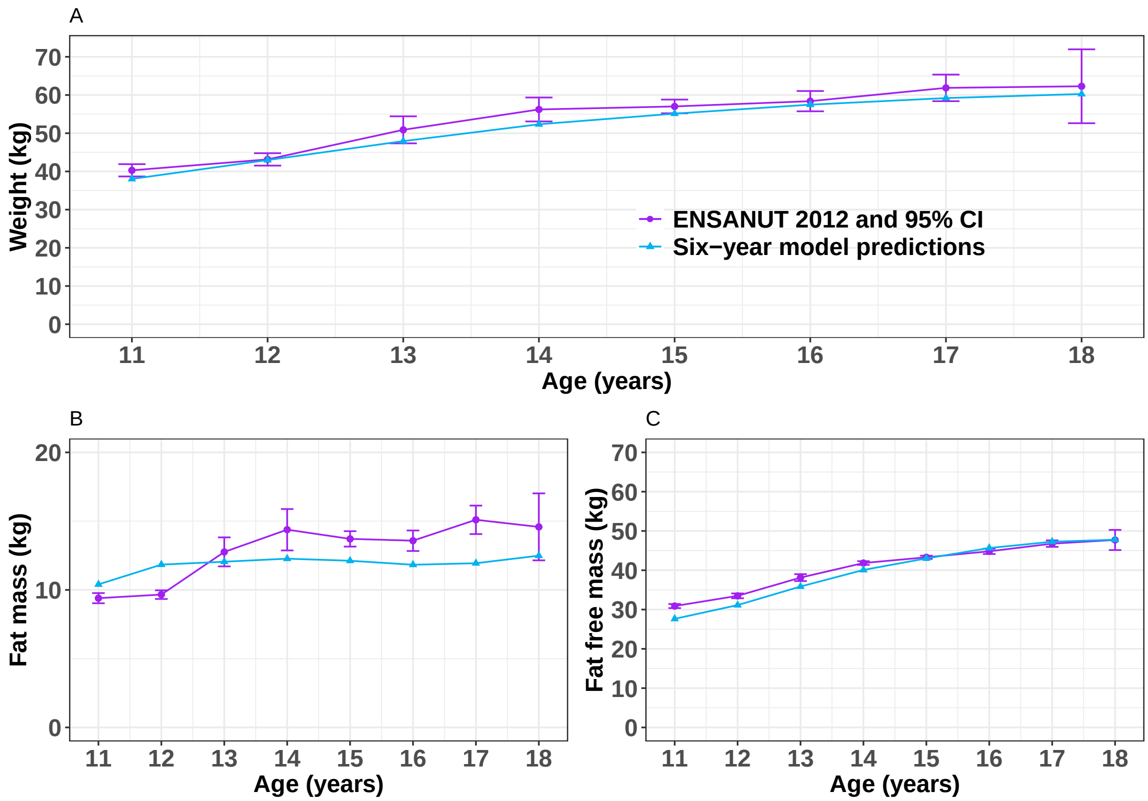
For validation purposes, we compared the mean body weights, FFM and FM by age (ages 6-18) from ENSANUT 2012 with the average one-year simulated weights from our weight model, using data from ENSANUT 2012 children ages 5-17. One-year predictions were consistent with the observed average weights for the corresponding ages in the ENSANUT 2012 data, with a 1.22 kg error (Figure 3).

Figure 3: **Reported (ENSANUT 2012) and model-simulated one-year average body weight (A), fat mass (B) and fat free mass (C) by age**



As an additional validation, we used the model and data from ENSANUT 2006 for children aged 5-12 to predict the average weight after 6-years (ages 11-18), to compare these predictions with the observed ENSANUT 2012 average weights, FM and FFM for ages 11-18. The 6-year predictions based on 2006 data were consistent with the observed average values in ENSANUT 2012, with an error of 2.10 kg in weight ($< 5\%$), 1.03 kg ($< 11\%$) in fat mass and 1.07 ($< 4\%$) in fat free mass (Figure 4).

Figure 4: **Comparison of average body composition data between the DCGO model six-year predictions with ENSANUT 2006 [4] children aged 5-12 and ENSANUT 2012 [8] reported average values. Weight (A), fat mass (B) and fat free mass (C).**



2 Sugar sweetened beverages consumption

We derived sugar sweetened beverages (SSB) consumption and total energy intake (TEI), using data from ENSANUT's 2012, 7-day semi-quantitative FFQ [9]. The individual amount of kcal/day from SSB was estimated as a fixed proportion of the reported TEI. This proportion was calculated for each individual k as:

$$propSSB_k = \frac{Reported\ SSB\ intake\ (k)}{Total\ energy\ intake\ (k)}. \tag{12}$$

The implementation of a 10% tax scenario yields to a purchase reduction of 0.4% in low and 13.2% in high SSB purchasers, respectively [10]. Based on this result we assumed the same reductions in SSB consumption. Applying a linear behavior, a tax of 20% would reduce $2 \cdot 0.4\%$ or $2 \cdot 13.2\%$ depending on the SSB consumption level and so on. We estimated the change in SSB energy intake attributable to taxation as follows:

$$\Delta SSB_k^{tax}(t) = 1 - propSSB_k(t) \cdot reduction^{\text{tax}}. \tag{13}$$

Finally, we estimated the new energy intake rate for each individual (i) using different taxes as:

$$\Delta I_{(k,ref)}^{\text{tax}}(t) = \big(I_{(k,ref)}(t) \cdot \Delta SSB_k^{\text{tax}}(t)\big). \tag{14}$$

2.1 Body weight estimation under baseline and taxed SSB scenarios

First we obtained the energy intake for every individual k in ENSANUT 2012 at time t as described in Section 1. Then we calculated the predicted weight $BW^{(k)}(t)$ using the weight change model:

$$BW_k^{\text{baseline}}(t) = BW_k^{\text{model}}\big(t + age_k;\ \text{Sex}_k, FM_k, FFM_k, I_{(k,\text{ref})}(t)\big). \tag{15}$$

To obtain the corresponding predicted weight under different SSB tax scenarios, the input for energy intake was considered as in equation (14), the new body weight was computed using:

$$BW_k^{\text{tax}}(t) = BW_k^{\text{model}}\big(t + age_k;\ \text{Sex}_k, FM_k, FFM_k, \Delta I_{(k,ref)}^{\text{tax}}(t)\big). \tag{16}$$

For our final outcome, we estimated each individual's body weight difference between no tax and different tax scenarios as:

$$\Delta BW_k^{\text{tax}}(t) = BW_k^{\text{baseline}}(t) - BW_k^{\text{tax}}(t). \tag{17}$$

3 Sensitivity analysis

We constructed a consumption-percent change Matrix Λ. This matrix, contains different combinations of taxation and caloric compensation scenarios, ranging from 0% to 100% by 10%. (Table 4). Each entry $\lambda_{i,j}$, corresponds to the percent of SSB reduction associated to different tax and compensation values and is calculated as follows:

$$\lambda_{i,j} = (i-1) \cdot \left(1 - \frac{(j-1)}{10}\right), \tag{18}$$

where $i = \{0\%, 10\%, 20\%, 30\%, \ldots, 100\%\}$, represents the tax values and $j = \{0\%, 10\%, 20\%, 30\%, , \ldots, 100\%\}$ the compensation values. Then, each entry $\lambda_{i,j}$ will be multiplied by the corresponding reduction for each individual's level of consumption.

Table 4: **Matrix Λ with percent reductions in SSB consumption, corresponding to tax and compensation augmentation.**

% Tax \ % Compensation	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
0	0	0	0	0	0	0	0	0	0	0	0
10	10	9	8	7	6	5	4	3	2	1	0
20	20	18	16	14	12	10	8	6	4	2	0
30	30	27	24	21	18	15	12	9	6	3	0
40	40	36	32	28	24	20	16	12	8	4	0
50	50	45	40	35	30	25	20	15	10	5	0
60	60	54	48	42	36	30	24	18	12	6	0
70	70	63	56	49	42	35	28	21	14	7	0
80	80	72	64	56	48	40	32	24	16	8	0
90	90	81	72	63	54	45	36	27	18	9	0
100	100	90	80	70	60	50	40	30	20	10	0

Using Matrix Λ, we calculated the change in SSB energy intake attributable to taxation as follows:

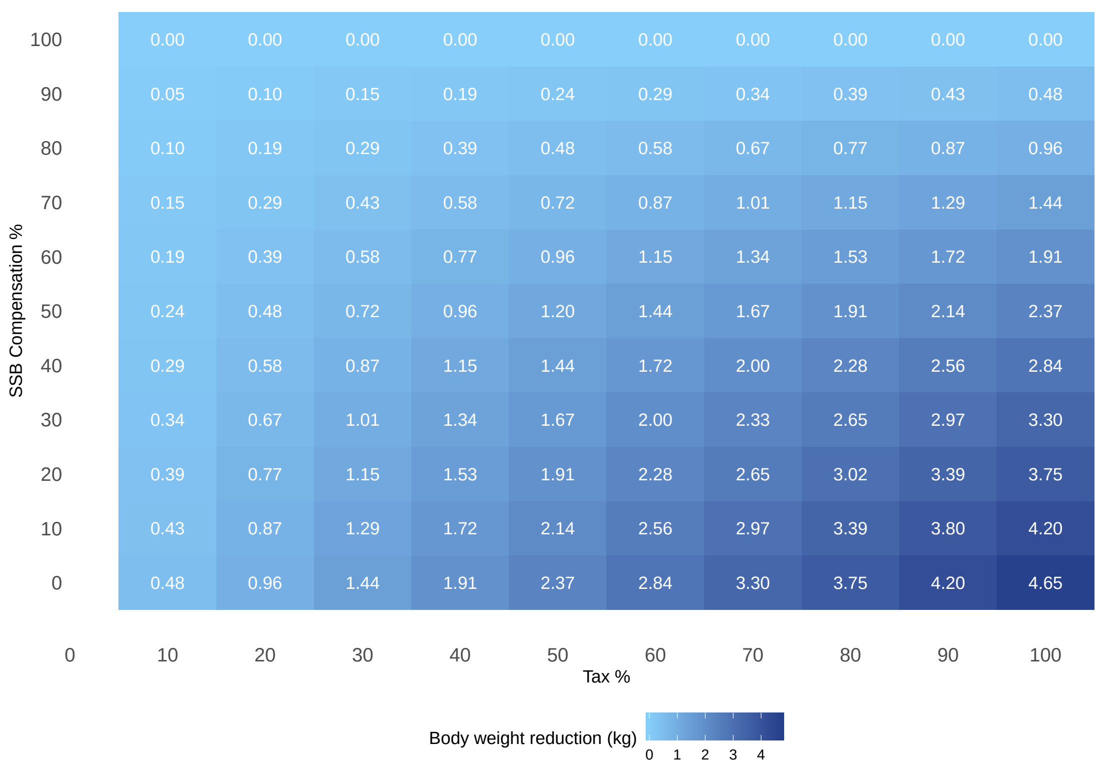
$$\Delta SSB^{k}_{(i,j)}(t) = 1 - propSSB_k(t) \cdot \lambda_{i,j}, \tag{19}$$

The new energy intake was estimated as in equation (14) and applied to the individual weight change model. Then, we estimated the values of the average body weight differences calculated as in section 2.1.

3.1 Long-term weight impact of the SSB-tax

As additional sensitivity analysis, we projected the potential long-term effect on weight of the implementation of the SSB tax. Figure 5 shows the results of our sensitivity analysis after 3 years of SSBs tax implementation. Overall, we observe that the potential effect of different tax and compensation scenarios on weight reduction could range between -0.48 kg with a 10% tax up to -4.65 kg with a 100% tax assuming a 0% caloric compensation. Nonetheless, even with a high caloric compensation (90%), we could still obtain weight reductions ranging from -0.05 kg to -0.48 kg with 10% or 100% taxes, respectively.

Figure 5: **Sensitivity analysis for estimated weight (Kg) change after 3 years based on different sugar reductions and compensation rates.**



4 Model Inputs

Input	Description	Value	Reference
Age	Age in years	5-18	ENSANUT 2012 [8]
Sex	male or female	0/1	ENSANUT 2012 [8]
Height	Height in meters	0.9-1.90 m	ENSANUT 2012 [8]
BW_0	Initial Body Weight	12-140 kg	ENSANUT 2012 [8]
BMI	Body mass index	10-58 $\frac{kg}{m^2}$	ENSANUT 2012 [8]
FM_0	Initial fatmass	$\frac{(1.51 \cdot BMI - 0.7 \cdot age - 3.6 \cdot sex + 1.4) \cdot BW}{100}$	ENSANUT 2012 [8]
FFM_0	Initial fat free mass	$BW - FM$	ENSANUT 2012 [8]
$\hat{\rho}_{FFM}$	Effective FFM energy density	$4.3(\frac{kcal}{kg^2})FFM(kg) + 837\frac{kcal}{kg}$	Model parameter from Hall et al. [1]
ρ_{FM}	FM energy density	$9.4\frac{kcal}{g}$	Model parameter from Hall et al. [1]
C	Forbes body composition	10.4kg$(\frac{\hat{\rho}_{FFM}}{\rho_{FM}})$	Model parameter from Hall et al. [1]
p	p-radio Energy partitioning	$\frac{C}{C+FM}$	Model parameter from Hall et al. [1]
K	Expenditure constant	male: 800 $\frac{kcal}{d}$ female: 700 $\frac{kcal}{d}$	Model parameter from Hall et al. [1]
η_{FM}	Cost of fat synthesis	180 $\frac{kcal}{d}$	Model parameter from Hall et al. [1]
η_{FFM}	Cost of fat free tissue synthesis	230 $\frac{kcal}{d}$	Model parameter from Hall et al. [1]
β	Adaptive thermogenesis	0.24	Model parameter from Hall et al. [1]
γ_{FM}	Metabolic rate of adipose tissue	4.5 kcal/kg/d	Model parameter from Hall et al. [1]
γ_{FFM}	Metabolic rate of fat-free tissue	22.4 kcal/kg/d	Model parameter from Hall et al. [1]
δ_{min}	Minimum physical activity	10 kcal/kg/d	Model parameter from Hall et al. [1]
δ_{max}	Maximum physical activity	male: 19 kcal/kg/d female: 17 kcal/kg/d	Model parameter from Hall et al. [1]
P	Time of half max. physical activity	12 years	Model parameter from Hall et al. [1]
h	Physical activity Hill coefficient	10	Model parameter from Hall et al. [1]

5 Algorithm and Implementation

To solve the system of differential equations (3), we used a 4th order Runge-Kutta algorithm (RK4)[11] with a stepsize $\Delta t = 1$. This weight model was implemented in the `bw` package in `R` using `Rcpp`[12, 13, 14, 15, 16]. The algorithm 1 contains the pseudo-code of the implementation.

Algorithm 1 Individual level weight change model

procedure WEIGHT CHANGE MODEL

Input:

n ▷ Number of individuals in sample

Years ▷ Number of years to run the model for

w_k ▷ Survey weight for k-th individual ($k = 1, \ldots, n$)

$I^{(i)}_{ref}(t)^{(k)}$ ▷ k-th individual's total energy intake reference ($k = 1, \ldots, n$, $0 \leq t \leq$ Years)

$\Delta SSB^{(k,\text{tax})}(t)$ ▷ k-th individual's energy intake reduction ($k = 1, \ldots, n$, $0 \leq t \leq$ Years)

$BW^{(k)}_{\text{init}}$ ▷ k-th individual's reported body weight ($k = 1, \ldots, n$)

$H^{(k)}_{\text{init}}$ ▷ k-th individual's reported height ($k = 1, \ldots, n$)

$\text{Age}^{(k)}_{\text{init}}$ ▷ k-th individual's reported age ($k = 1, \ldots, n$)

$\text{Sex}^{(k)}$ ▷ k-th individual's sex ($k = 1, \ldots, n$)

for k **in** 1 **to** n **do**

$\text{BMI}^{(k)}_{\text{init}} \leftarrow BW^{(k)}_{\text{init}} / \big(H^{(k)}_{\text{init}}\big)^2$

$\text{Body Fat }\%^{(k)}_{\text{init}} \leftarrow 1.51 \cdot \text{BMI}^{(k)} - 0.70 \cdot \text{Age}^{(k)}_{\text{init}} - 3.6 \cdot \mathbb{I}_{\text{Sex}^{(k)}==\text{`Male'}} + 1.4.$

$FM^{(k)}_{\text{init}} \leftarrow \big(\text{Body Fat }\%^{(k)}_{\text{init}}\big) \cdot BW^{(k)}_{\text{init}}$

$FFM^{(k)}_{\text{init}} \leftarrow BW^{(k)}_{\text{init}} - FM^{(k)}_{init}$

$\Delta I(t)^{(k,\text{tax})}_{ref} \leftarrow \big(I^{(k)}_{ref}(t) \cdot \Delta SSB^{(k,\text{tax})}(t)\big).$

for tax **in** $[0, 10, 20, 30, 40]$ **do**

Runge Kutta 4 do

Calculate $\hat{\rho}^{(k)}_{FFM}$ and $p^{(k)}$ from (3).

Calculate $g^{(k)}(t)$ from (4).

Interpolate linearly the values of Table 3 to calculate $I^{(k)}_{ref}$ as in (7).

Calculate $E^{(k,\text{tax})}(t)$ from (5).

Aproximate $\frac{dFFM}{dt}^{(k,\text{tax})}$ and $\frac{dFM}{dt}^{(k,\text{tax})}$ as in (3).

end Runge Kutta 4

Calculate $BW^{(k,\text{tax})}(t) \leftarrow FM^{(k,\text{tax})}(t) + FFM^{(k,\text{tax})}(t).$

$\Delta BW^{(k,\text{tax})} \leftarrow BW^{(k,0)}(365 \cdot \text{Years}) - BW^{(k,\text{tax})}(365 \cdot \text{Years})$

end for

end for

for tax **in** $[10, 20, 30, 40]$ **do**

for cat **in** [Males, Females, Overall] **do**

$\overline{\Delta BW}^{(\text{tax})}_{\text{cat}} = \sum_{i=1}^{n} w_i \cdot \Delta BW^{(i,\text{tax})} \cdot \mathbb{I}_{\text{cat}}$

end for

end for

end procedure

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