**SUPPLEMENTARY MATERIALS**

**Long term wet bioenergy resources in Switzerland: Drivers and projections until 2050**

**Authors:** Vanessa Burga, b, Gillianne Bowmana, Stefanie Hellwegb, Oliver Theesa

a Swiss Forest, Landscape and Snow Federal Research Institute WSL, Zürcherstrasse 111, CH-8903 Birmensdorf, Switzerland

b Swiss Federal Institute of Technology Zürich (ETH Zürich), Institute of Environmental Engineering, John-von-Neumann-Weg 9, CH-8093 Zürich, Switzerland

Table of contents

[S1. Pairwise correlations 2](#_Toc12969437)

[S2. Time series analyses 11](#_Toc12969438)

[S3. Monte Carlo simulations 18](#_Toc12969439)

[S4. References 25](#_Toc12969440)

# Pair wise correlations

For each biomass type, correlations between possible drivers (explanatory variables) were tested using R. These were calculated using the “chart.Correlation()” function from the “PerformanceAnalytics” R-Package. Not all variables expected to influence the biomass availability could be tested depending on the availability of databases (e.g. waste management framework, technology development). Only linear correlations can be identified with this method. The following tables (S1–S4) provide the following information:

* Correlation coefficient (r) - The strength of the relationship,
* p-value - significance of the relationship (codes 0 '\*\*\*', 0.001 '\*\*', 0.01 '\*').

**S1.1. Animal Manure**

The following variables were tested:

* The total number of animals as livestock units LSU (1996-2016 [1]).
* The number of animals per specie (1996-2016 [2]).
* The quantity of animal energy in TJ produced yearly (Agristat, 2008-2015 [3]).
* The milk and meat consumption (2007-20015 [4]).
* The milk (1996-2016 [5]) and the meat production (2007-2016 [6]).
* The total agricultural surface (1996-2016 [7]).
* The yearly production in Mio CHF for the agriculture and forestry branch and for the food and tobacco branch (1997-2016 [8]).
* The total number of hours spend in the pasture, which is expected to increase similarly to past data (12% for cattle between 2002 and 2010). As we have only three data points (2002, 2007 and 2010) [9], the correlations are not statistically significant but percent of animal with access to pasture and number of days spent in the pasture are showing an increase across the three dates.
* The estimated quantity of N, P and K, e.g. through mineral, recycled and other fertilizers (2008-2015 [3]).

Table S1 Animal manure – Correlation coefficient and level of significance of tested variables (data available for 10 to 20 years) - p-value significance codes 0 '\*\*\*' 0.001 '\*\*' 0.01 '\*'





Since the number of animals of separate categories did not explain the amounts of manure well (except for a few which clearly do not drive overall manure availability, such as goat number), it appeared more appropriate to summarize the distinct animal numbers in total livestock units for the simulation of the future resources quantity. We only test the total amount of manure and not the manure produced per type of animal. For LSU, a positive correlation comprised between 0.68 and 0.74 to the various nutrients in manure could be established.

Indeed, the total number of animals in LSU is per se closely linked to the production of manure but show no significant correlation with any of the factors tested. Some non-relevant but highly significant correlations (e.g. number of goats with meat (0.91\*\*\*) and milk (0.89\*\*\*) production) seems to indicated that other factors tested here are not relevant for manure production.

**S1.2. Agricultural crop by-products**

Variables tested:

* Cereal production (1996-2016 [10]).
* The quantity of vegetal energy in TJ produced yearly (2008-2015 [3]).
* The quantity of fresh vegetables and vegetables to keep (2008-2015 [3]).
* The surface area of the different crop types (1996-2016[7]).

Table S2: Agricultural crop by-products – Correlation coefficient and level of significance of all tested variables - p-value significance codes 0 '\*\*\*' 0.001 '\*\*' 0.01 '\*'



As the different surface area per crop are strongly correlated, we only used the total agricultural area in Switzerland, which has shown a slight decrease in the past 20 years (-3%). Links with other quantities are less direct, even though the correlation can be quite strong. With today state of the art handling of crops, only cereal residues (chaff) are of importance. The yearly cereal production is correlated with the total agricultural area (0.74\*\*\*). Therefore, the total agricultural area was used as a driver in the estimation of the future biomass potential of agricultural by-products.

**S1.3. Organic fraction of household garbage & green waste from household   
and landscape**

As both biomass types are strongly linked, their possible drivers were tested together.

Variables tested:

* Total household and municipal garbage collected per capita in kg (1996-2016 [11]).
* Household garbage thermally treated per capita in kg (1996-2016 [11]).
* Household garbage separately collected per capita in kg (1996-2016 [11]).
* Percentage of household and municipal garbage recycled (1996-2016 [12]).
* Plant material separately collected per capita in kg (1996-2016 [12, 13]).
* Number of inhabitants in Switzerland (1996-2016 [14]).
* Growth Domestic Product per capita and for the country (1996-2016 [15]).
* Industrial production index in percent (1990-2011 [16]).
* Private consumption (1996-2016 [17]).

Considering the total garbage collected per capita as an indication of the temporal evolution of the organic fraction of household garbage, we found strong positive correlations with population growth (0.79\*\*\*) and the GDP per capita (0.92\*\*\*), and private consumption (0.93\*\*\*). The same correlations are strong for green waste (plant material separately collected) with population (0.89\*\*\*), GDP per capita (0.88\*\*\*), and private consumption (0.89\*\*\*). In both cases, we chose to use total private consumption as it seems to be the factor most directly linked to the consumption of the households and already includes the evolution of the population.

Table S3: Org. fraction of household garbage & green waste from household and landscape – Correlation coefficient and level of significance of all tested variables.   
p-value significance codes 0 '\*\*\*' 0.001 '\*\*' 0.01 '\*'



**S1.4. Commercial and industrial organic waste**

Variables tested:

* Household and municipal garbage collected per capita in kg (1996-2016 [11]).
* Household and municipal garbage thermally treated per capita in kg (1996-2016 [11]).
* Household and municipal garbage separately collected per capita in kg (1996-2016 [11]).
* Percentage of household and municipal garbage recycled (1996-2016 [12]).
* Plant material separately collected per capita in kg (1996-2016 [12]).
* Paper separately collected per capita in kg (1996-2016 [13]).
* The yearly production in Mio CHF in total and for the different branches separately: agriculture and forestry, the food and tobacco, printing industry, pharmaceutical industry, retailers and restauration industry (1997-2016 [8]).
* Number of inhabitants in Switzerland (1996-2016 [14]).
* Growth Domestic Product per capita (1996-2016 [15]).
* Industrial production index in percent (1990-2011 [16]).

Table S4: Commercial and industrial organic waste – Correlation coefficient and level of significance of all tested variables. p-value significance codes 0 '\*\*\*' 0.001 '\*\*' 0.01 '\*'



Most industrial categories were strongly positively correlated to population, GDP per capita and production index, which are all three highly correlated. We chose the production index as it is the most applicable to industry (28% increase between 1996 and 2011). Regarding industrial and commercial waste, the yearly production in Mio CHF for each branch was correlated with the general production index of the secondary sector: agriculture and forestry (-0.31), food and tobacco (0.92\*\*\*), printing industry (-0.80\*\*\*), pharmaceutical industry (0.93\*\*\*), retailers (0.92\*\*\*) and restauration industry (0.93\*\*\*). The production index was also correlated with separated garbage waste (0.92\*\*\*).

**S1.5 Sewage sludge**

Regarding sewage sludge, no variables could be tested. The values were calculated using only the population equivalent as an explanatory variable, and the base year and possible technology changes for their additional uncertainties.

# Time series analyses

The available past data series of five identified drivers were analyzed in order to extrapolate their possible trend up to 2050 (for the other drivers, no previous data series were available). We used an ARIMA model in R to find the values and uncertainties of these five drivers in 2035 and 2050. These were calculated using the “arima()” and “predict()” functions from the “Forecast” R-Package. This type of model uses: (AR) the dependent relationship between an observation and a number of lagged observations; (I) differentiation of raw observations (e.g. subtracting an observation from an observation at the previous time step) to make the time series stationary; (MA) the dependency between an observation and a residual error from a moving average model applied to lagged observations. Each of these components are explicitly given as a parameter, noted ARIMA(p,d,q). We have: p: number of lag observations included in the model (lag order); d: number of times that the raw observations are differenced (degree of differencing); q: size of the moving average window (order of moving average). The precise model (e.g. values for arima(p,d,q)) was chosen according to the residual distribution, the AIC (Akaike information criterion) values and literature references, while aiming to use the simplest model per driver. Finally, the simulated series from the estimated coefficients was visually inspected, as a last check before a model was called appropriate.

Each model is described below and an example of R script is provided in a separate file.

Table S5: Time series from 1996 to 2016 [1, 7, 8, 14, 15]

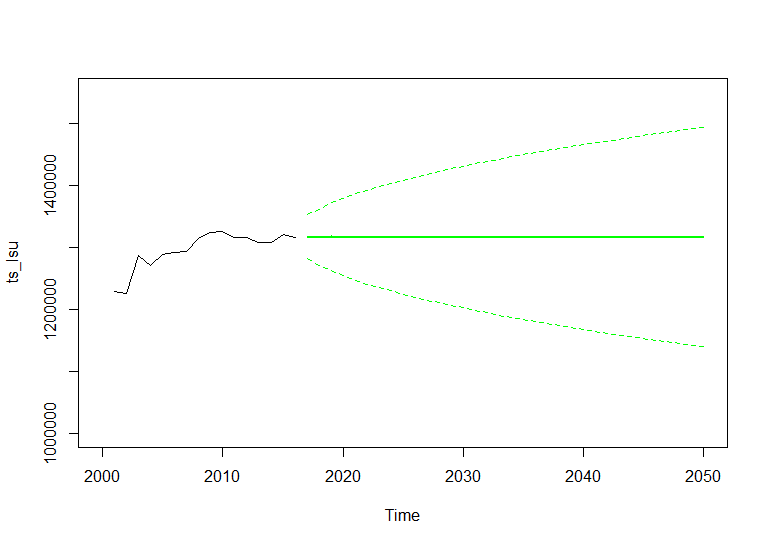


Table S6: Time series projections for 2035 and 2050 from the ARIMA model



**NUMBER OF ANIMALS IN LIVESTOCK UNITS**

ARIMA (1, 1, 1): The past data appear to have a certain trend thus we chose d=1. By examining the residuals of ACF and PACF plots ARIMA(1,1,1) was chosen (see Figure S2). AIC was also examined (342.7) but tended to select more complex specification of the model, resulting to similar mean forecast but considerably higher uncertainties. Hence, we decided to use the more parsimonious model (1,1,1). Visual inspection of the resulting series confirmed the choice of the model to be appropriate.

  
Figure S1: Number of animals (in livestock units LSU), time series forecast with ARIMA (black: past, green: forecast, dotted line: standard deviation)

**LSU**

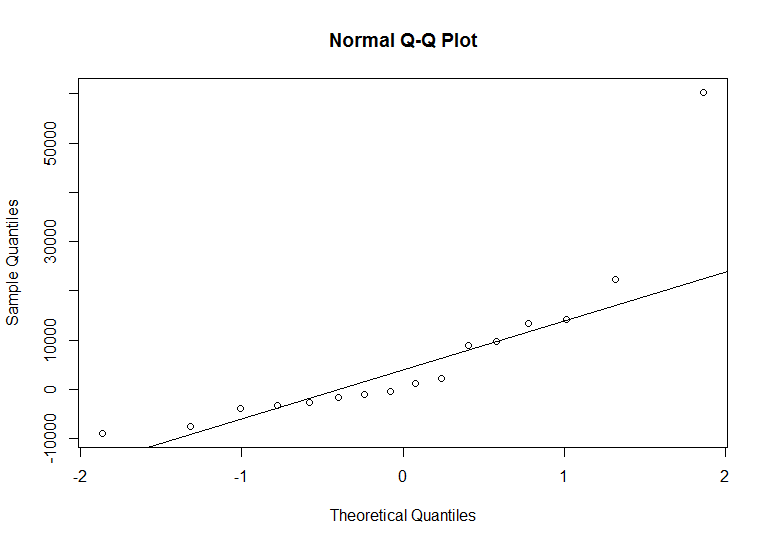
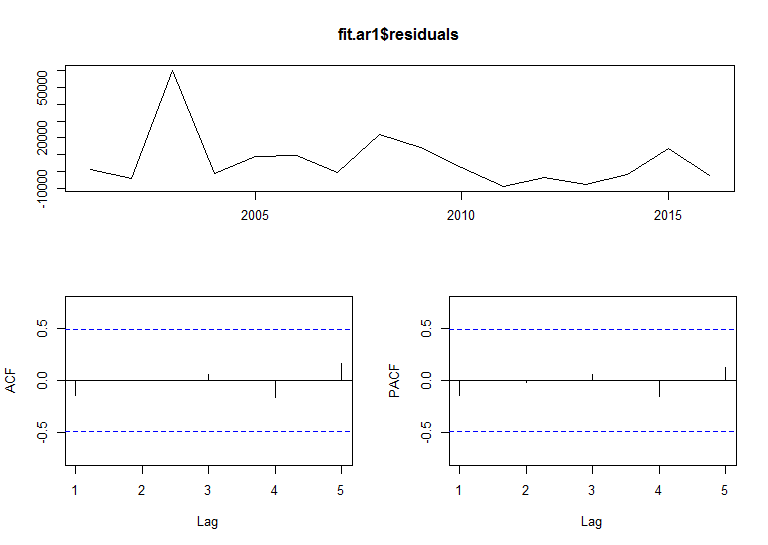
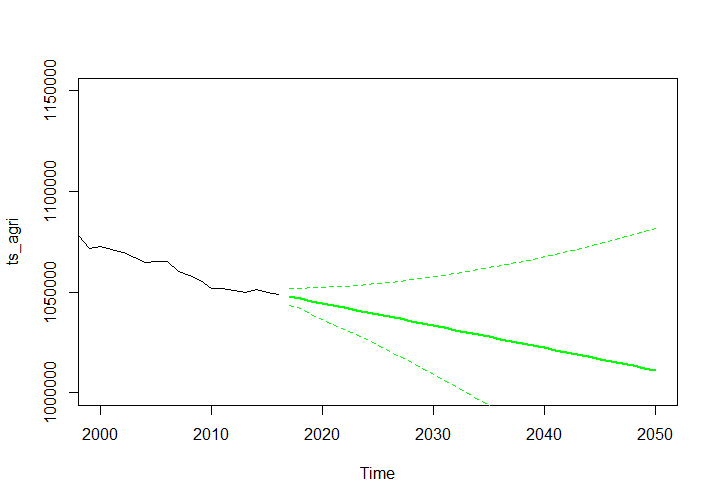
 

Figure S2: Number of animals (in livestock units LSU), time series forecast with ARIMA (residuals of the fitted model)

**NUMBER OF HECTARES OF AGRICULTURAL AREA**

ARIMA (1, 2, 1): The past data appear to have a trend (non-stationarity). By examining the residual plots ARIMA(1,2,1) was chosen (see Figure S4). AIC was also calculated and confirmed these model specifications which showed the lowest value (356.7). Visual inspection of the resulting series confirmed the model to be appropriate.



**Agricultural area (ha)**

Figure S3: Agricultural area (in hectare), time series forecast with ARIMA (black: past, green: forecast, dotted line: standard deviation)

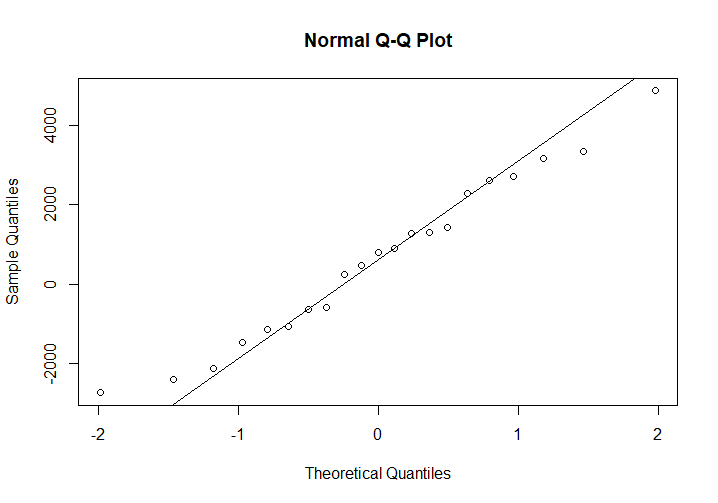
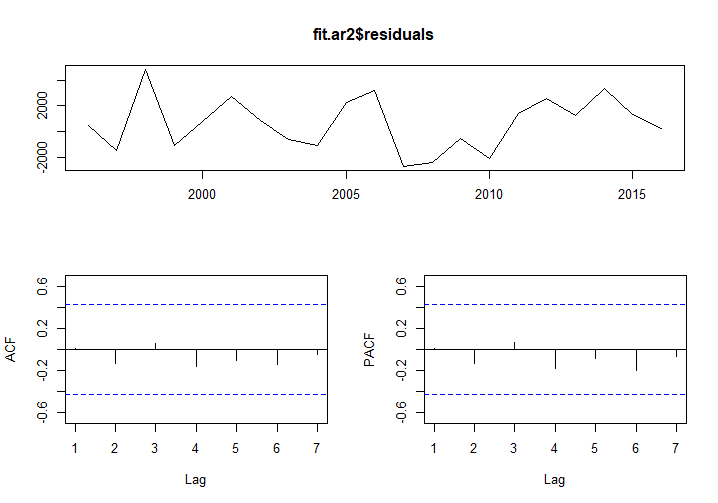
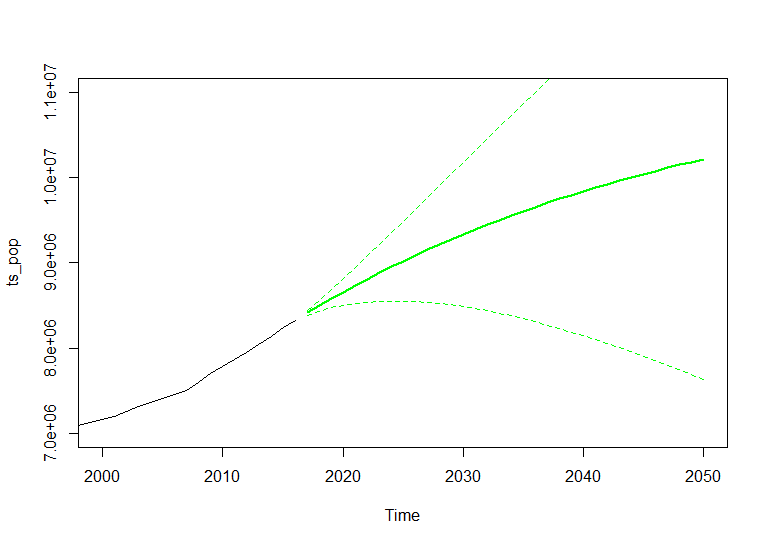
 

Figure S4: Agricultural area (in hectare), time series forecast with ARIMA (residuals of the fitted model)

**POPULATION IN NUMBER OF INHABITANTS**

ARIMA (2, 1, 1): The past data appear to have a clear trend. By examining the residuals from ACF and PACF ARIMA(2,1,1) was chosen (see Figure S6). These specifications gave the second lowest AIC from the different models tested (preferring a more complex model). However we decided to use the more parsimonious model (2,1,1), with estimations closer to the literature [19]. Visual inspection of the resulting series confirmed the choice of the model to be appropriate.



**Number of inhabitants**

Figure S5: Population (in number of inhabitants), time series forecast with ARIMA (black: past, green: forecast, dotted line: standard deviation)

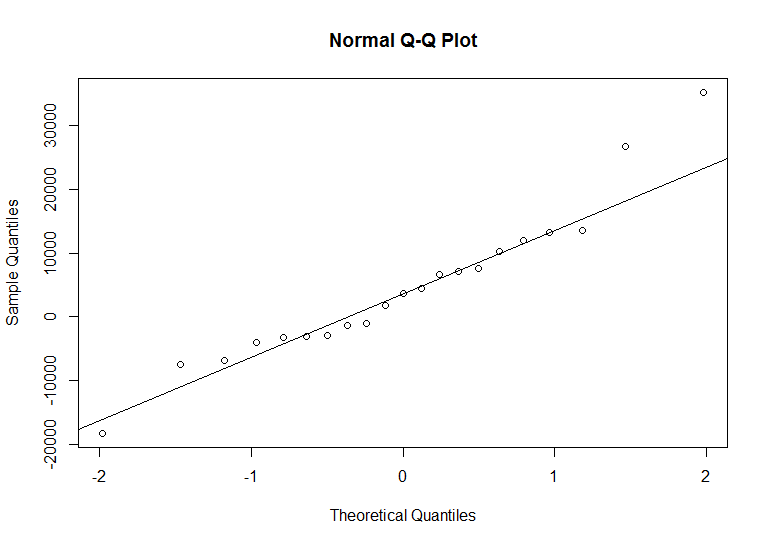
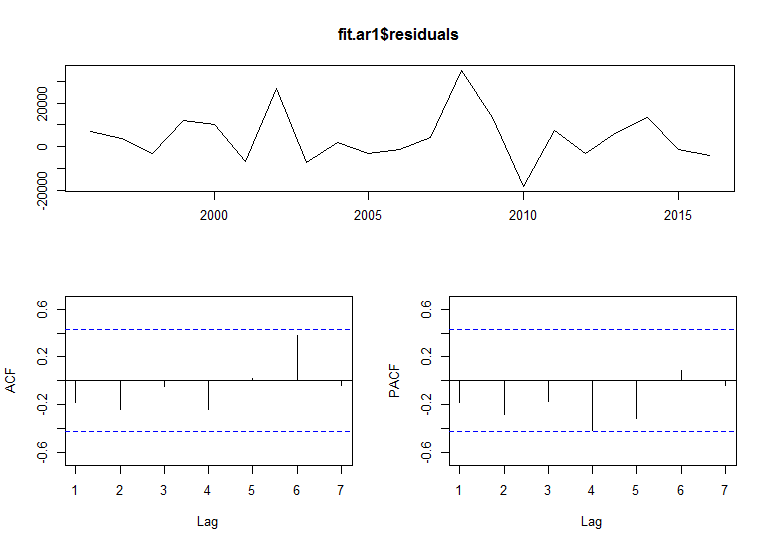
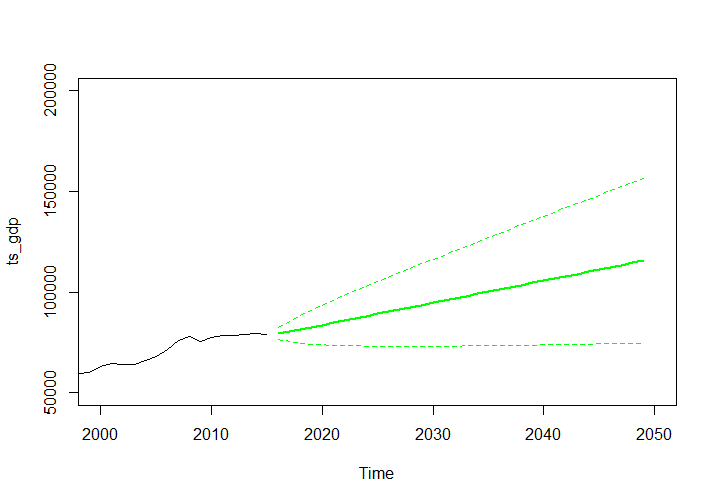
 

Figure S6: Population (in number of inhabitants), time series forecast with ARIMA (residuals of the fitted model)

**GDP PER CAPITA IN CHF**

ARIMA (1, 2, 1): The past data appear to have a trend (non-stationarity). By examining the residual plots ARIMA(1,2,1) was chosen (see Figure S8). AIC was also calculated and confirmed these model specifications which showed the lowest value from the different models tested. Visual inspection of the resulting series confirmed the model to be appropriate.



**GDP per capita (CHF)**

Figure S7: Gross domestic product (GDP) per capita (in CHF), time series forecast with ARIMA (black: past, green: forecast, dotted line: standard deviation)

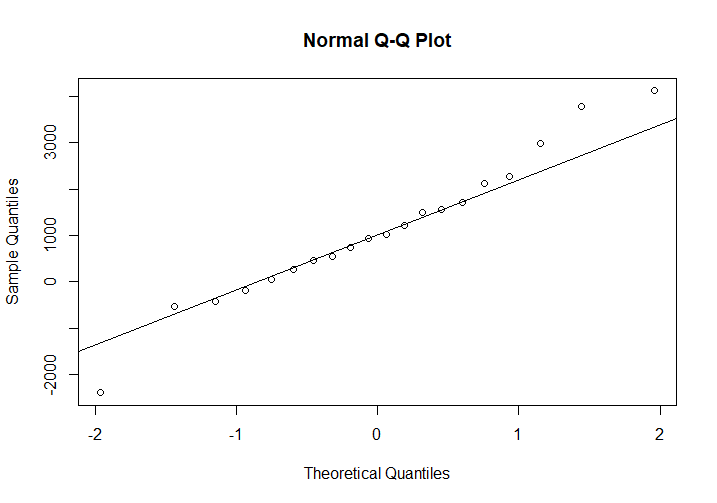
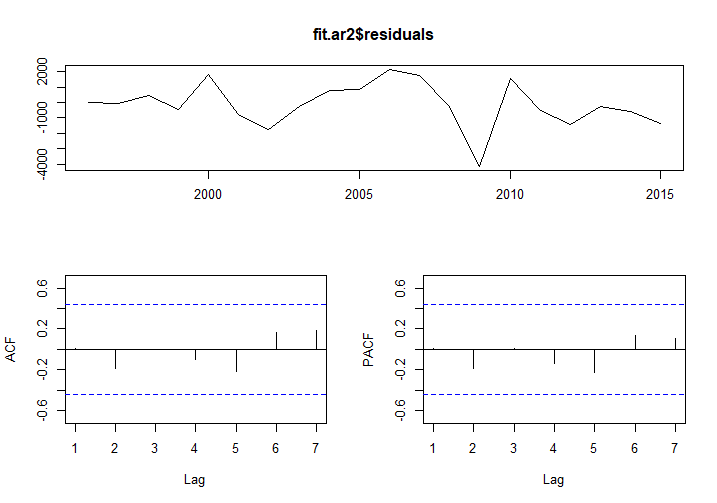
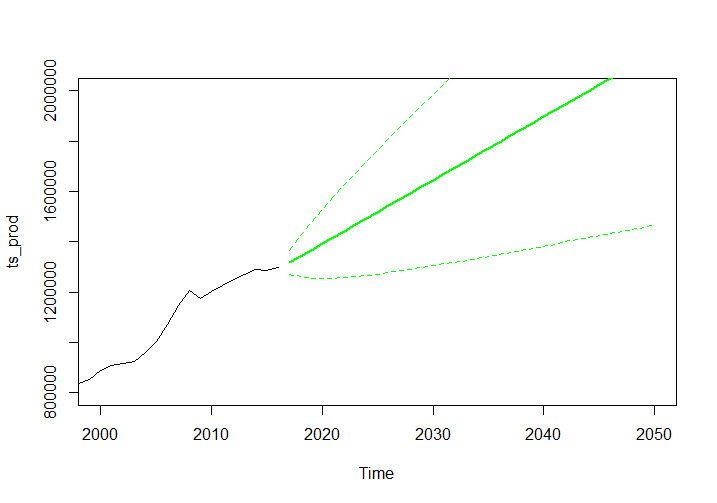
 

Figure S8: Gross domestic product (GDP) per capita (in CHF), time series forecast with ARIMA (residuals of the fitted model)

**PRODUCTION IN CHF**

ARIMA (1, 2, 1): The past data appear to have a trend (non-stationarity). By examining the residual plots ARIMA(1,2,1) was chosen (see Figure S10). AIC was also calculated and confirmed these model specifications which showed the lowest value. Visual inspection of the resulting series confirmed the model to be appropriate.



**Industrial production (CHF)**

Figure S9: Industrial production (in CHF), time series forecast with ARIMA (black: past, green: forecast, dotted line: standard deviation)

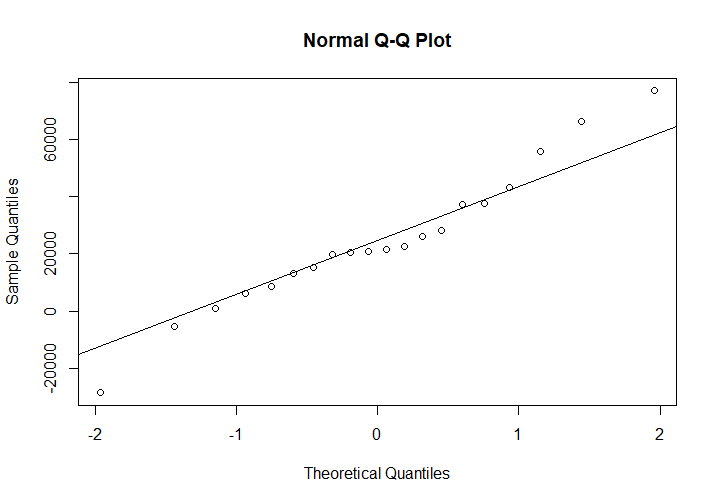
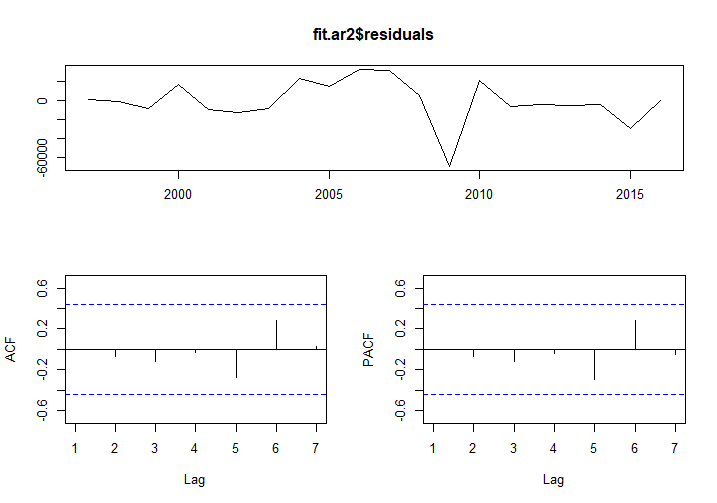
 

Figure S10: Industrial production (in CHF), time series forecast with ARIMA (residuals of the fitted model)

# Monte Carlo simulations

The estimated drivers trends were used to build the matrices used in the Monte Carlo simulations. Also, an uncertainty of 3% was considered for the calculated potential values of the base year 2014 for the six wet biomass types. We provide below the matrices used for the simulations. The following figures (S1 – S6) show the histogram of the simulated outcomes.

**ANIMAL MANURE**

Regarding the uncertainty, each factor variance is taken into account. All the co-variances are set to 0, as no correlation could be expected to be causal. Hence e.g. for 2035, we have the following complete variance-covariance matrix:

Var-Covar(ManureT2035)=



The first column refers to uncertainty of the biomass amount of the base year. The 3 following columns refer to the drivers that influence the theoretical potential. The 2 last ones refer to the sustainable potential.

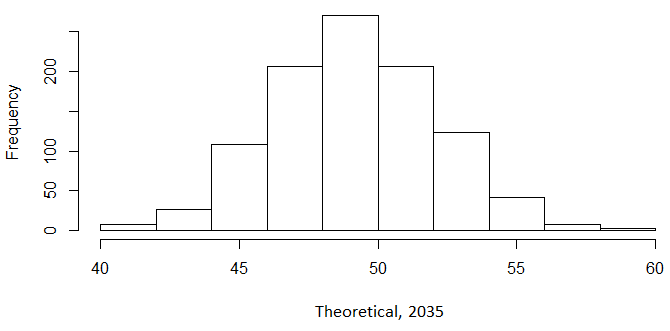
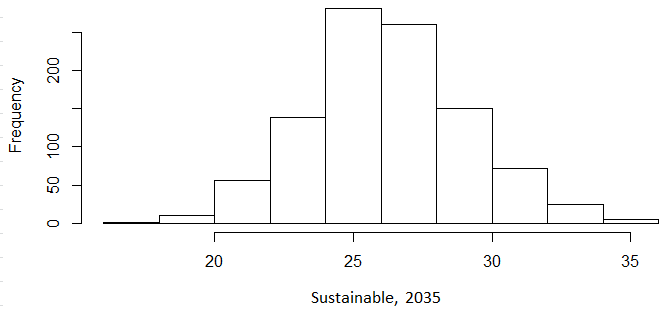
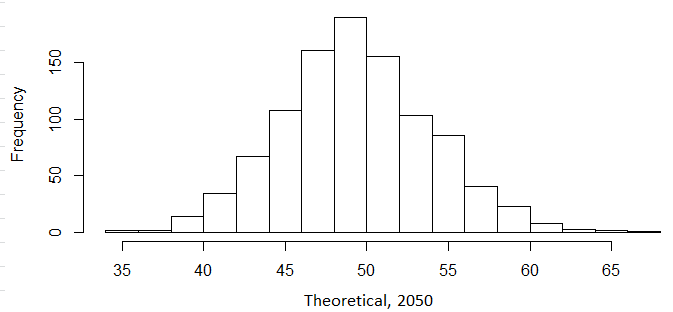
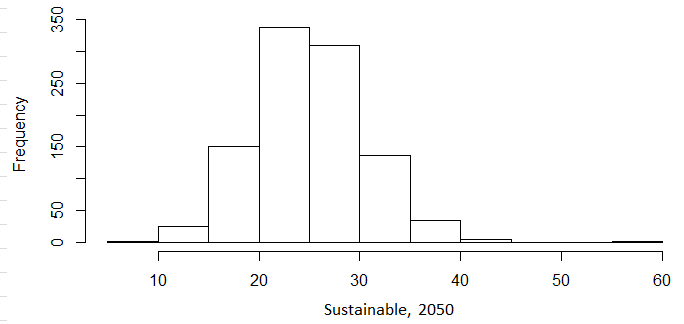
   

Figure S11: Animal manure ‑ Distribution of the simulated values for the theoretical and sustainable potential (2035, 2050); 1000 runs

**AGRICULTURAL CROP BY-PRODUCTS**

Regarding the uncertainty, each factor variance is taken into account. All the co-variances are set to 0, as no correlation could be expected to be causal.

Hence e.g. for 2035, we have the following complete variance-covariance matrix:

Var-Covar(ManureT2035)=



The first column refers to uncertainty of the biomass amount of the base year. The 3 following columns refer to the drivers that influence the theoretical potential. The last one refers to the sustainable potential.

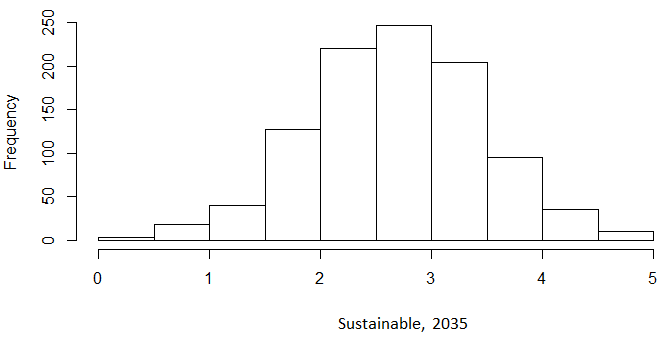
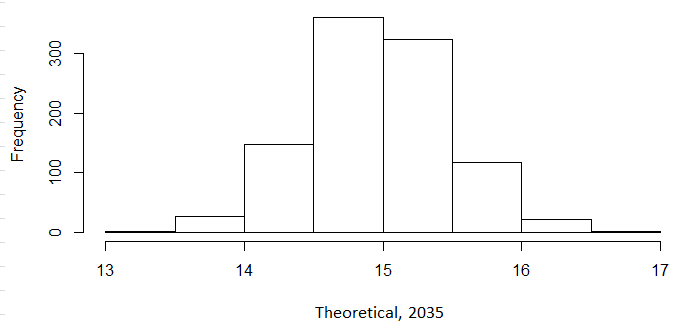
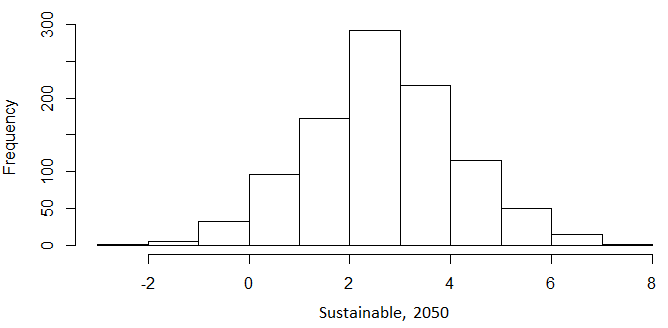
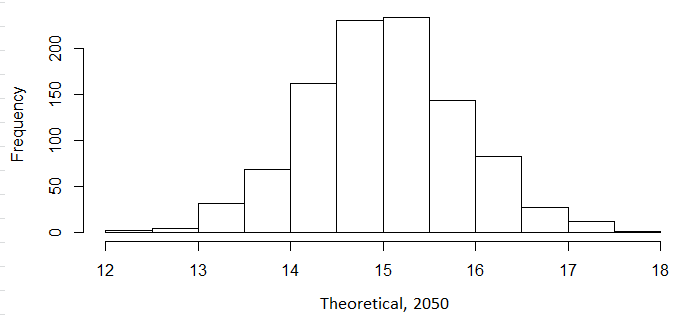
 

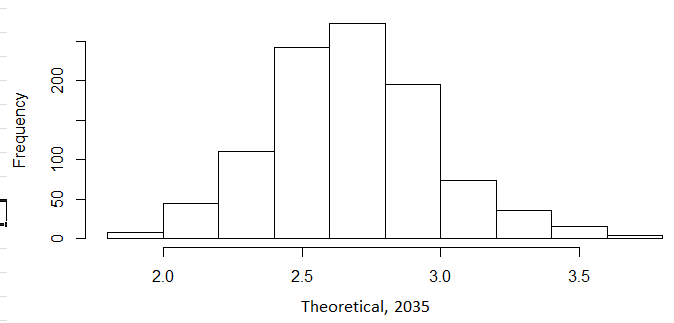
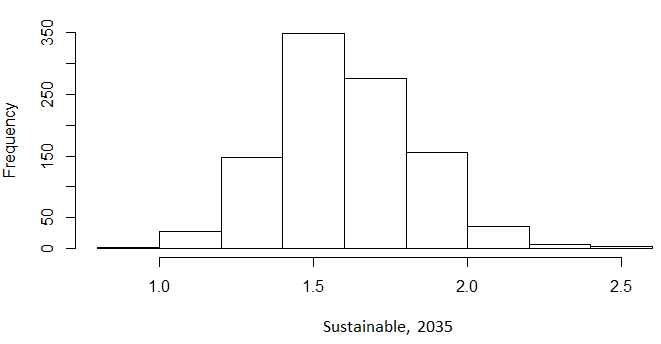
Figure S12: Agricultural crop by-products ‑ Distribution of the simulated values for the theoretical and sustainable potential (2035, 2050); 1000 runs

**ORGANIC FRACTION OF HOUSEHOLD GARBAGE**

Regarding the uncertainty, each factor variance is taken into account. There is also a correlation between the organic fraction and the total amount of garbage per capita. Hence e.g. for 2035, we have the following complete variance-covariance matrix:

Var-Covar(GarbageT2035)=



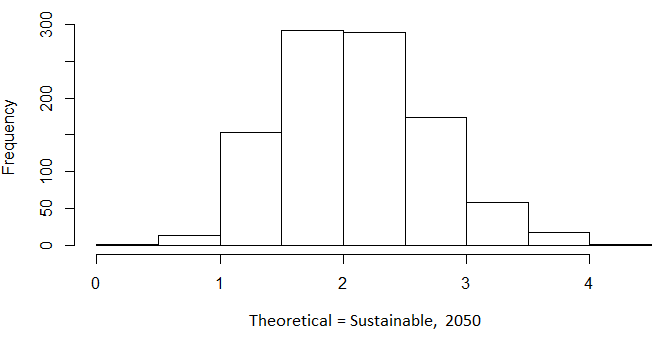


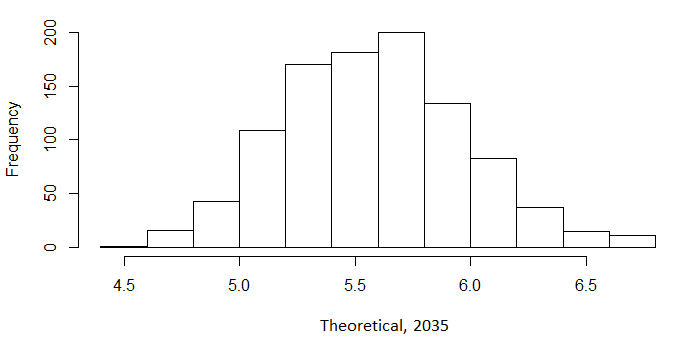
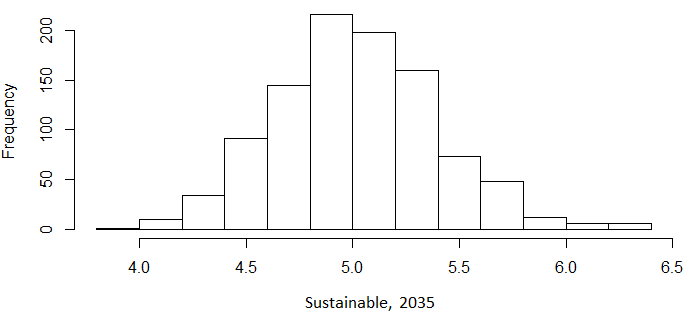
Figure S13: Org. fraction of household garbage ‑ Distribution of the simulated values for the theoretical and sustainable potential (2035, 2050); 1000 runs

**GREEN WASTE FROM HOUSEHOLD AND LANDSCAPE**

Regarding the uncertainty, each factor variance is taken into account. There is also a correlation between the green waste amount and the green waste collected per capita within the municipalities. Hence e.g. for 2035, we have the following complete variance-covariance matrix:

Var-Covar(GreenWasteT2035)=



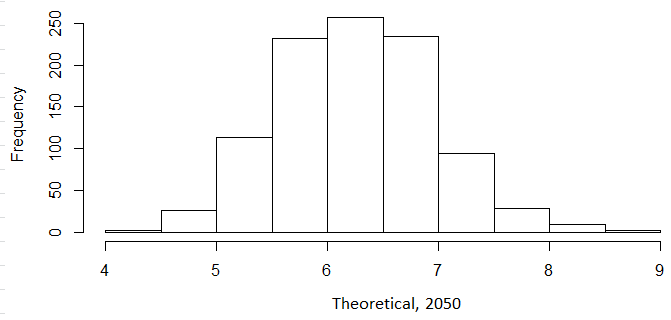
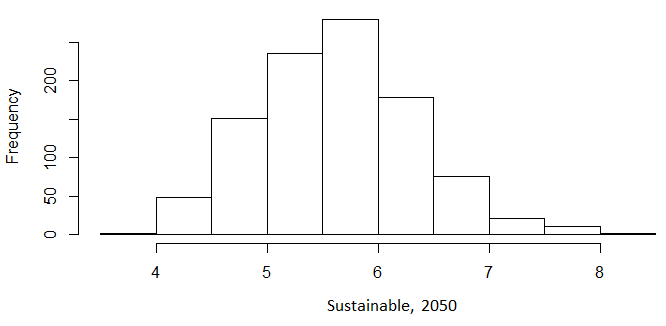
 

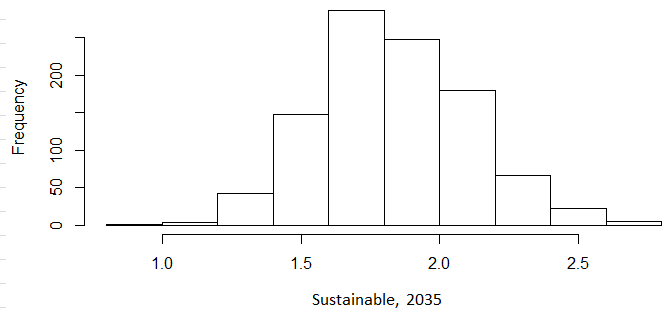
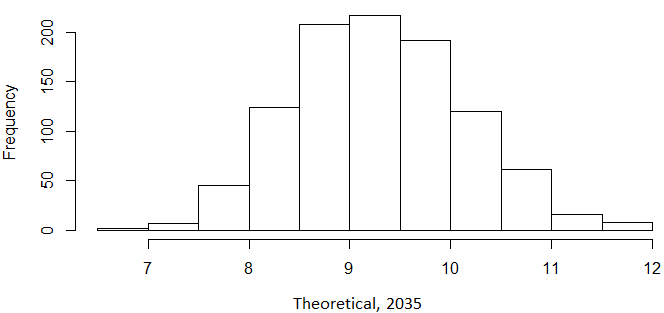
Figure S14: Green waste from household and landscape ‑ Distribution of the simulated values for the theoretical and sustainable potential (2035, 2050); 1000 runs

**COMMERCIAL AND INDUSTRIAL ORGANIC WASTE**

Regarding the uncertainty, each factor variance is taken into account. All the co-variances are set to 0, as no correlation could be expected to be causal. Hence e.g. for 2035, we have the following complete variance-covariance matrix:

Var-Covar(IndustryT2035)=





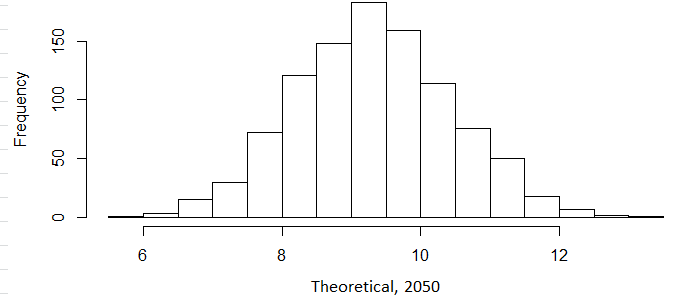
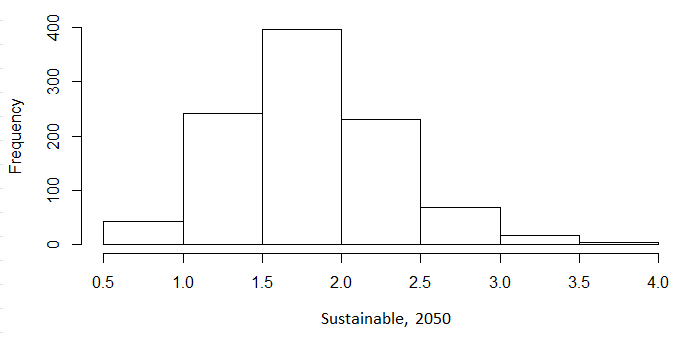
 

Figure S15: Commercial and industrial org. waste ‑ Distribution of the simulated values for the theoretical and sustainable potential (2035, 2050); 1000 runs

**SEWAGE SLUDGE**

Regarding the uncertainty, each factor variance is taken into account. All the co-variances are set to 0, as no correlation could be expected to be causal. Hence e.g. for 2035, we have the following complete variance-covariance matrix:

Var-Covar(SewageT2035)=



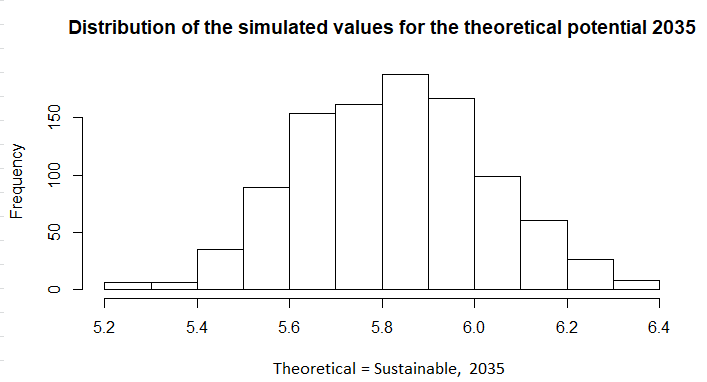
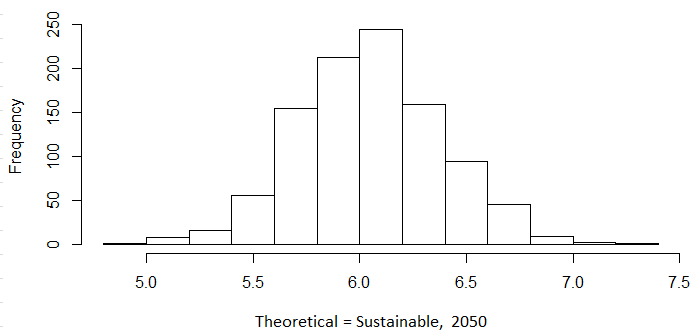
 

Figure S16: Sewage sludge ‑ Distribution of the simulated values for the theoretical and sustainable potential (2035, 2050); 1000 runs

Table S7: Future biomass availability for 2035 and 2050 as theoretical and sustainable potentials in primary energy in PJ



# References

1. BLW *Agrar Bericht 2017*; 2017; p 460.

2. BFS Entwicklung der Nutztierbestände. <http://www.bfs.admin.ch/bfs/portal/de/index/themen/07/03/blank/ind24.indicator.240205.2402.html> (access date 01.08.2016)

3. Agristat *Statistische Erhebungen und Schätzungen über Landwirtschaft und Ernährung*; 2016; p 269.

4. BFS, Entwicklung des Nahrungsmittelverbrauch in der Schweiz. Je Kopf und Jahr (je-d-07.06.02). In <https://www.bfs.admin.ch/bfs/de/home/statistiken/kataloge-datenbanken/tabellen.assetdetail.5866399.html>, 2016.

5. BLW *Evaluation des données sur la production laitière, année civile 2017*; <https://www.blw.admin.ch/blw/fr/home/nachhaltige-produktion/tierische-produktion/milch-und-milchprodukte.html>, 2018.

6. Proviande *Der Fleischmarkt im überblick 2016* <https://www.proviande.ch/fr/services-statistique/statistique/publications/archive.html>, 2017; p 64.

7. BFS, Landwirtschaftliche Nutzfläche. Ohne Sömmerungsweiden 1985-2016. In <https://www.bfs.admin.ch/bfs/de/home/statistiken/kataloge-datenbanken/tabellen.assetdetail.7106327.html>, 2016.

8. BFS, Compte de production par branches (50 branches) (je-f-04.02.03.01). In <https://www.bfs.admin.ch/bfs/de/home/statistiken/volkswirtschaft/volkswirtschaftliche-gesamtrechnung/produktionskonto.assetdetail.5966197.html>, 2018.

9. Kupper, T.; Bonjour, C.; Achermann, B.; Rihm, B.; Zaucker, F.; Menzi, H. *Ammoniakemissionen in der Schweiz 1990-2010 und Prognose bis 2020*; BAFU, Bundesamt für Umwelt: 2013; p 110.

10. BFS, Production de céréales, évolution (07.02.03.01.01). In <https://www.bfs.admin.ch/bfs/fr/home/statistiques/catalogues-banques-donnees/tableaux.assetdetail.6369498.html>, 2017.

11. BFS, Siedlungsabfälle (02.03.02.10). In <https://www.bfs.admin.ch/bfs/de/home/statistiken/kataloge-datenbanken/tabellen.assetdetail.4082480.html>, 2017.

12. BFS, Siedlungsabfälle-Separatsammelquote - Anteil der separat gesammelten Abfälle im Verhältnis zur Gesamtmenge der verursachten Siedlungsabfälle - In Prozent In <https://www.bfs.admin.ch/bfs/de/home/statistiken/nachhaltige-entwicklung/monitoring-ziele-agenda-2030/alle-nach-themen/12-konsum-produktion/abfall-separatsammelquote.assetdetail.5626310.html>, 2018.

13. BAFU, AB099\_Separat gesammelte Abfälle\_20180814\_BAFUIndikatorDatenblatt1. In <https://www.bafu.admin.ch/bafu/it/home/temi/rifiuti/stato/indicatori/indikator-abfall/_jcr_content/par/externalcontent.external.exturl.xlsx/aHR0cHM6Ly93d3cuaW5kaWthdG9yZW4uYWRtaW4uY2gvUHVibG/ljL0V4cG9ydD92ZXJzaW9uSWQ9MzI5MyZjb25maWc9MQ==.xlsx>, 2018.

14. BFS, Bilan de la population résidente permanente de 1861 à 2016 (su-f-01.02.04.05). In <https://www.bfs.admin.ch/bfs/en/home/statistics/catalogues-databases/tables.assetdetail.5886176.html>, 2018.

15. BFS, Bruttoinlandprodukt pro Einwohner, lange Serie, 1948-2016 (4.02.01.05). In <https://www.bfs.admin.ch/bfs/de/home/statistiken/volkswirtschaft/volkswirtschaftliche-gesamtrechnung/bruttoinlandprodukt.assetdetail.6028921.html>, 2017.

16. BAFU, QU068\_Industrielle Produktion\_20180814\_BAFUIndikatorDatenblatt1. In <https://www.bafu.admin.ch/bafu/de/home.html>, 2014.

17. BFS, Hauptindikatoren der Volkswirtschaftlichen Gesamtrechnung (je-d-04.02.01.04). In <https://www.bfs.admin.ch/bfs/de/home/statistiken/volkswirtschaft/volkswirtschaftliche-gesamtrechnung.assetdetail.6067513.html>, 2018.

18. Burg, V.; Bowman, G.; Erni, M.; Lemm, R.; Thees, O., Analyzing the potential of domestic biomass resources for the energy transition in Switzerland. *Biomass Bioenerg* **2018,** 111, 60-69.

19. BFS *Szenarien zur Bevölkerungsentwicklung der Kantone der Schweiz 2015-2045*; 2016; p 7.