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Modeling greenhouse gas emissions from the forestry sector – the case of Latvia

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Abstract. A system dynamics model for assessing the greenhouse gas (GHG) emissions from forestry and forest land is presented in the paper. The model is based on the IPCC guidelines for national GHG inventories and includes the main elements of the forestry sector, i.e. changes in the living biomass, dead organic matter and soils. The developed model allows simulating various policies and measures implemented and decisions made, and their impact on change in the GHG emissions. Various scenarios of potential development in the medium-term planning were simulated till 2030 to assess their impact on the GHG emissions. It is found that the most sustainable option would be use of wood processing waste for production of e.g. wood chips or some added-value products. The case of Latvia is selected for simulations, as forests compose about 52% of the country's area. Nevertheless, by changing specific parametric values the model can be adapted and applied for estimation and analysis of GHG emissions from forestry in other countries, as well.

Key words: GHG emissions, forestry, living biomass, wood waste, system dynamics.

INTRODUCTION

Latvia is the fourth most forested country in Europe. About 52% of the country's total area is covered by forests, which is 3.5 million hectares (State Forest service). Over the last century, Latvian forest areas have nearly doubled – in 1923, the forest area accounted for only 27% of the country's territory. The forest area continues to increase, though on a slower rate (Forest sector in Latvia). The forest areas have increased mainly due to the natural and artificial afforestation of agricultural land (State Forest service). Usually, the naturally afforested land contains generally more inferior stands.

An indicator characterizing the increasing forest resources in Latvia is the fact that the annual increase in wood stock is triple of the increase of the forest areas (State Forest service). Thus, it can be stated that the forest land increases as a result of targeted forestry activities. Over the last decade, the annual amount of round wood extracted has been around 12 million m^3 (State Forest service). The amount is smaller than the natural increment, thus the Latvian forestry can be considered as sustainable.

The forestry sector is directly associated with the greenhouse gas (GHG) emissions that are released and removed simultaneously. Latvia is one of the few countries where more emissions are removed than emitted (LNIR, 2014). This is due to the comparatively large forest areas and living forest biomass that is able to remove emissions released by other sectors (agriculture, energy, industry, waste management etc.). However, in recent years the emission amount removed has a tendency to decrease. In 2012, the net GHG emissions from the forestry sector were equal to -13,099 Gg CO_2 eq. (LNIR, 2014) being practically the lowest level since 1990. The reason for that is the increase in forest felling. As a result not only the capacity of the living biomass is reduced, but the amount of forest processing waste is increased. Therefore, it is important to assess the possibilities for increased emission removals or at least balancing them at the current level.

The Intergovernmental Panel on Climate Change (IPCC) has established a methodology for estimating GHG emissions from various sectors, including forestry (IPCC, 2006). The IPCC guidelines facilitate making an inventory of the GHG emissions generated in the past. However, the forecasting options are limited, especially when an effect of various decisions, measures and policy instruments on GHG emission dynamics has to be assessed. Thereof, the aim of this paper is to present an alternative tool for estimating the forestry's GHG emissions. The tool is developed by using the system dynamics (SD) method that allows capturing the relationship between cause and effect of a complex dynamic system as the forestry is (Dace et al., 2014). In addition, the aim of the study was to test the possibilities to limit the increase in the net GHG emissions of the forestry sector.

SD was developed by Jay Forrester in 1950's (Forrester, 1958) and has, since then, been applied to a diverse set problems (Sterman, 2000), e.g. collection of waste portable batteries (Blumberga et.al., 2015), development of a low-carbon strategy (Blumberga et.al., 2014), switching to renewable energy sources (Romagnoli et.al., 2014), etc. To our knowledge, the studies where SD has been applied to assess forestry's GHG emissions are scarce. Machado et.al. (Machado et al., 2013) have used SD to evaluate the growth and carbon stock of eucalyptus forests in Brazil. They have considered the four main flows, i.e. land use, wood stock, carbon stock and forest land increase. In addition SD has not been used to evaluate an impact on emissions from land use, land-use change and forestry (LULUCF). Though, other types of models have been created. E.g. CBM-CFS3 (Carbon Budget Model of the Canadian Forest Sector) has been developed based on the IPCC methodology to assess carbon dynamics in forestry and land-use change in Canada (Kurtz et al., 2009). Thus, we believe, that the SD model built in this study is a unique tool that can be adapted to other countries similar to Latvia, as the structure of the system remains, and only specific parametric values have to be changed.

METHODOLOGY

A SD model was developed based on the IPCC guidelines for national GHG inventories (IPCC, 2006). Thus, a static linear methodology for assessing national GHG emissions was combined with dynamic modeling of non-linear complex systems provided by SD. The model was built in two separate major blocks, i.e. agriculture and forestry (see Fig.1). GHG emissions from the processes of livestock enteric fermentation, manure management and soil cultivation were simulated in the agricultural sub-model. Whereas, modeling of the GHG emissions from the forestry sector included emission removals by the living biomass (various tree species) and emissions from decomposition of dead organic matter and organic and mineral soils.

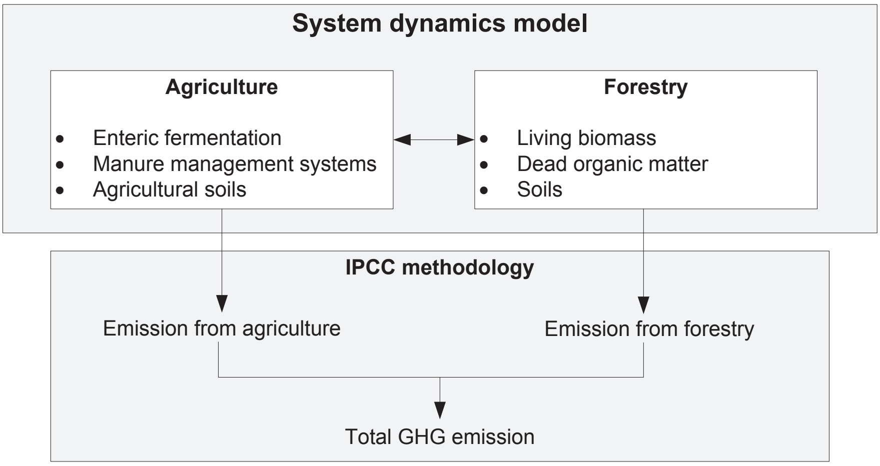

Figure 1. Logical framework of the methodology applied.

In SD, stock-and-flow diagrams are used to build the structure of the studied real-world system. That allows capturing the essential activities and accumulations of the system, as the drivers of activity are represented as information-feedback processes (Buch et al., 2008). The system's performance is determined by the system's structure which, on its turn, is created by the feedbacks.

In our study, *Powersim Studio 8* software environment was used to develop the model. Numeric values of certain quantitative parameters were estimated from the historic statistical data bases on GDP, prices, land stocks, agricultural and forestry products etc. In addition, interviews with experts were used to assess accuracy of the processes and future developments simulated. In the model, all the information reflects the situation in Latvia. Nevertheless, many of the case-specific numeric parameter values may be changed to represent the situation in some other country, as the structure of the model is similar in many countries.

In our model, the emissions were simulated for the time period from 2005 until 2030. That allowed us to compare the simulation results with the historical observed tendency (back-casting) and to analyze the future development under various policy decisions. It has to be noted, that the aim of SD modeling is to present the trend of dynamic behavior of the real system, not to give projection of exact values (Sterman, 2000). Thus, the focus is on relationships rather than on the precision of the simulated parametric values.

Agriculture is directly associated with climate change issues on environmental, economic and social dimensions. Agricultural activities emit greenhouse gases that, on their turn, influence the agricultural productivity. The GHG emissions in the agricultural sector arise from livestock farms as a result of processes of livestock enteric fermentation and management and storage of manure. Emissions arise also from cultivation and fertilization of agricultural soils. Agricultural sector is problematic with respect to GHG emissions, as within the sector options for GHG emission abatement are limited. Hence, the most efficient option is to limit agricultural activities themselves. Obviously, abandoning the idea of streaming towards increased agricultural productivity is not a solution, and mechanisms mitigating the negative environmental impacts (GHG emissions) have to be found. Conversely, forests work as removers of the GHG emissions from the atmosphere. As 52% of the area of Latvia is covered by forests (State Forest service), all of the local agricultural emissions, theoretically, are removed. Still, in the last decades, intense felling has been carried, thus steadily reducing the amount of emissions removed. In addition, wood waste is created. Gradual decomposition of the wood waste and litter, wood burning, and also forest soils generate emissions. All these interactions are simulated with the developed model.

The model (see Fig. 2) simulates the dynamics of the forest area of each tree species and how it is split in young forest stand, mature forest and clearings. Also, the wood stock, its increment, as well as wood mortality and decomposition are simulated. In addition, the model simulates the amount of above- and below-ground wood waste generated. Thus, the results for forest land's GHG emissions and removals are estimated.

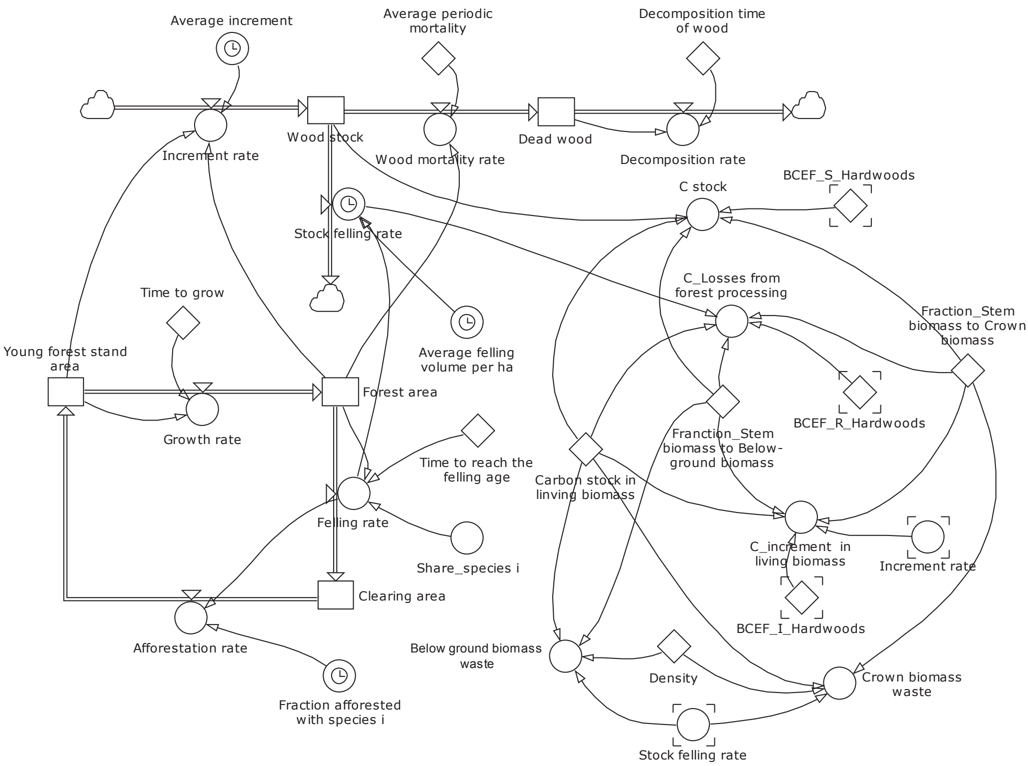

Figure 2. Stock-and-flow diagram of the wood stock and waste model.

The simulation is started in 2005. Thereof, the initial state of each stock in the model corresponds to the value reported in statistical databases for 2005. Then, the flows are defined. For each tree species, a certain amount of time necessary to grow and reach the felling age. Yet, felling largely depend on the market price of the particular wood species, as that determines the interest in cutting and selling the wood. Hence, the felling rate is determined as:

$$r_{f_i} = \frac{A_{Fi} \cdot \left[\frac{e^{\alpha \cdot P_i}}{\sum e^{\alpha \cdot P_n}} \right]}{T_{fi}} \qquad (1)$$

where: r_{fi} – felling rate of species i, ha yr^{-1}; A_{Fi} – forest area of species i, ha; e = 2.718 – the base of the natural logarithm (Euler number); α – coefficient that determines the steepness of the curve of share of wood species as a function of the market price; P_i – market price of wood of species i, EUR m^{-3}; P_n – market price of wood, EUR m^{-3}; T_{fi} – time to reach the felling age, yr; n – wood species (pine, spruce, birch, oak, ash, black alder, grey alder, aspen and other species).

Knowing the average amount of wood cut per hectare and multiplying it with the felling rate r_f, the stock felling rate is determined. The wood stock accumulates the difference between the stock increment rate flowing in and the stock felling rate and wood mortality rate flowing out of the stock (see Eq.2).

$$S_i = \int (r_{ii} - r_{sfi} - r_{mi})(t) \cdot dt + S_i' \qquad (2)$$

where: S_i – stock of wood species i, m^3; r_{ii} – increment rate of species i, m^3 yr^{-1}; r_{sfi} – stock felling rate of species i, ha yr^{-1}; r_{mi} – wood mortality rate of species i, m^3 yr^{-1}; S'_i – initial stock of wood species i, m^3.

The estimated S, r_i and r_{sf} are used to calculate the annual carbon stock and carbon increment in living biomass and carbon loss from forest processing according to the IPCC guidelines for national GHG inventories (IPCC, 2006). The calculated parameters are then used to estimate removals of GHG emissions.

r_{sf} is also used to assess the wood waste generated by cutting the trees. It is assumed that 80% of wood wastes are left in forests. 5% of the wastes left in forests are burned. Whereas, the remaining part decays during a 20 year period. The annual carbon stock in forest litter is estimated assuming that the decomposition rate is 0.1% yr^{-1} (Berg, 2000). The resulting values are used to calculate the emissions from forests.

The emissions and removals from forests are affected not only by the processes happening in the forest, but also by the total area of land available for forests. Since 1990s, the area of forest land has been steadily increasing in Latvia (Forest sector in Latvia). The main reason for that was the overgrowth of agricultural land, as a result of its abandoning. Since implementation of the support payments for management of agricultural land (single area payments, direct payments and complementary national direct payments), the abandoning and overgrowth has descended, thus reducing the increase rate of the forest land area. In the model, the transition from agricultural to forest land was simulated by building two stocks – the stock of agricultural land and the stock of forest land (see Fig. 3). Agricultural land becomes the forest land when bush and trees reach 5 m height and occupy 20% of the area considering the crown projection (The Law on Forests). In addition, it is considered that 20 years are necessary to change the land-use type (IPCC, 2006). Moreover, there is an indicated maximum area that can be taken by forests. It is assumed that the indicated area equals the sum of forest land area and 30% of the agricultural land area that was registered in 2005. Thus, the area of forests in Latvia cannot exceed 3,566,328 ha. The rate of transition is calculated as follows:

$$r_t = IF(L_F^{max} > L_F), THEN(L_A \cdot (1 - F_m)/T_o), ELSE(0) \quad (3)$$

where: r_t – transition rate from agricultural land to forest land, ha yr[-1]; L_F^{max} – indicated maximum area of forest land, ha; L_F – area of forest land, ha; L_A – area of agricultural land, ha; F_m – fraction of managed agricultural land; T_o – time necessary for agricultural land to overgrow and become the forest land, yr.

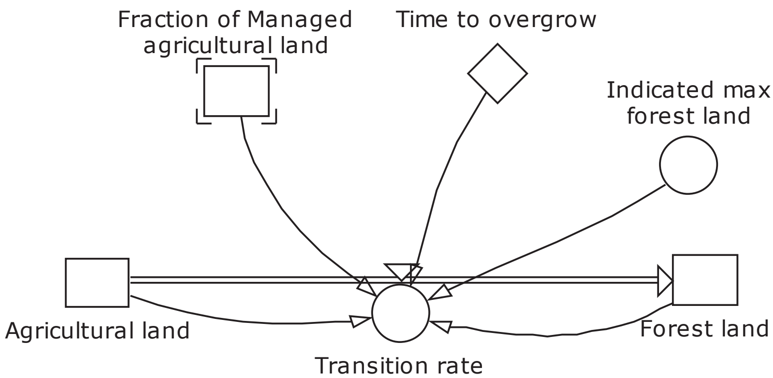

Figure 3. Stock-and-flow diagram of the overgrowth of agricultural land.

The parametric values used in the model are shown in Tables 1 and 2 (only parameters not indicated in the IPPC guidelines (IPCC, 2006) are shown).

In order to assess the dynamics of the GHG emissions and removals from forest land, several scenarios were developed. First, the base scenario (reference scenario) was developed to observe the potential dynamics of the system provided that the forestry and agricultural sectors will continue to develop following the historically observed tendency. Then, based on the results of the base scenario, various decisions and measures were tested to assess their impact on net GHG emission rates from the forest land.

In scenario I, an option of increased use of the above-ground (crown) biomass waste for production of wood chips is assessed. Currently, only small amount of forest processing wastes are used for wood chips' production. This is due to the high production costs and low market price. The wood processing wastes frequently are polluted with impurities (e.g. sand) which determines their low quality. Most of the wood chips produced in Latvia are exported, and demand exists only for high-quality wood chips.

Table 1. Wood species-specific parametric values of the model

Parameter	Unit	Value									Source
		Pine	Spruce	Birch	Aspen	Black alder	Grey alder	Oak	Ash	Other	
Average increment	$m^3\ ha^{-1}\ yr^{-1}$	8.3	11.7	7.8	10.4	9.9	8.9	5.7	5.7	12.0	LNIR, 2014
Average periodic mortality	$m^3\ ha^{-1}\ yr^{-1}$	2.4	3.3	2.3	3.1	2.6	0.8	4.6	4.6	1.2	LNIR, 2014
Wood density	$t\ m^{-3}$	0.38	0.36	0.47	0.40	0.41	0.41	0.41	0.41	0.41	LNIR, 2014
Time to grow	yr	40	40	20	20	20	10	40	40	20	The Law on Forests
Time to reach felling age	yr	70	41	31	21	51	51	61	41	41	The Law on Forests
Greenery mass	$kg\ m^{-3}$	78.0	117.7	-	-	-	-	-	-	-	Daugavietis et. at., 2012, Stibe, 1976
Initial wood stock	$m^3\ 10^6$	248.1	88.82	159.1	23.9	15.0	31.1	2.2	3.7	1.2	State Forest service
Initial dead wood amount	$m^3\ 10^6$	2.65	2.21	2.24	0.64	0.46	0.25	0.11	0.19	0.09	State Forest service
Initial young forest stand area	$ha\ 10^3$	118.0	273.3	98.2	25.5	5.9	7.6	0.7	5.8	0.9	State Forest service
Initial forest area	$ha\ 10^3$	928.4	242.0	733.6	75.1	68.6	182.2	9.3	12.5	5.8	State Forest service
Initial clearings area	$ha\ 10^3$	11.12	9.46	11.26	4.75	0.76	5.98	0.04	0.12	0.0	State Forest service

Table 2. Other parametric values of the model

Parameter	Unit	Value	Source
Technologically obtainable fraction of above-ground biomass	%	70	Adamovics et al., 2009
Technologically obtainable fraction of below-ground biomass	%	60	Adamovics et al., 2009
Average litter decomposition rate	$\%\ da^{-1}$	0.1	Berg, 2000
Initial agricultural land area	$ha\ 10^6$	2.45	CSB, 2015
Initial forest land area	$ha\ 10^6$	2.82	CSB, 2015
Indicated max forest land	$ha\ 10^6$	3.56	State Forest service

It is assumed that only 70% of the wood processing waste in clearings can be used for production purposes, as 30% are considered as the technological loss (Adamovics et al., 2009). However, should there be favorable conditions (e.g. increased demand) allowing economically feasible realization the technologically available crown biomass, the wood processing waste would be cut considerably. Thus, the emissions from the decay of the dead organic matter would be reduced. That forms the base for the scenario I.

In scenario II, a situation where also below-ground biomass wastes (stumps) are used is assessed. Technologically it is possible to extract up to 60% of the below-ground biomass (Adamovics et al., 2009). So far, in Latvia, utilization of the stumps for production of wood chips has not been practiced, as more easily collectable wood has been available. Still, stumps are valuable and hitherto undervalued resource. It should be noted that a specific extraction technology has to be applied (Silava, 2008). Besides, the stump extraction is allowed only in certain types of forests.

Another option to reduce the wood processing wastes is to use the greenery (needles and small branches) of conifers for manufacturing products. In Latvia, the greenery in small amounts is used for production of needle extract (Pollution permit, 2010). Yet, before also high-quality forage has been produced. In the recent years, use of the greenery for production of insulation materials has been intensely studied (Muizniece et al., 2015). In the last case, a large amount of the material would be required. Thereof, collection and use of the greenery (considering the technological loss of 30%) is simulated in scenario III.

In scenario IV, the dynamics in GHG emissions is assessed assuming that policy instruments are implemented and changes in legislation are made that limit forest felling by 20%. E.g. introduction of felling quota could serve as such an instrument. As a result, emissions generated during decomposition of wood waste would decrease (as there would be less waste). Moreover, removal of GHG emissions would increase as the wood stock would not be depleted on such a rate as before. Introduction of the instrument would allow slowing the rate of stock felling to prevent the stock reduction to a critical level and endangering biodiversity.

Similarly, an influence of introducing a tax on wood felling is assessed in scenario V. The tax would increase the wood price, thus decreasing the demand for wood. That would allow reduction of amount of wood processing waste and preservation of the living biomass that removes emissions. It is simulated that the prices increase by 20% as a result of tax introduction.

Changes in transition rate from agricultural land to forest land are simulated in scenario VI. In the National Development Plan of Latvia for 2014–2020 (NDP, 2012), an ambitious target for management of agricultural land is set, i.e. a more intensive, though sustainable use of each hectare of the agricultural land. According to the Plan, 95% of the agricultural land should be managed by 2020. In 2013, 85% of the agricultural land was managed. Thus, it is planned to decrease the area of land left unmanaged and overgrown with bush and natural forest. As a result, the increase rate of forest land area will lower, biodiversity will decrease, and the amount of GHG emissions from agricultural activity will rise. Therefore, it is necessary to assess how emissions from forest land would change upon realization of the target set in the Plan.

In the model, implementation of the simulated decisions and measures is started from 2016. An exception is the intensification of management of the agricultural land that should have been started in 2014, already.

RESULTS AND DISCUSSION

The results of the base scenario show that, in the forest sector, a tendency exists for emissions to increase and removals – to decrease (see Fig. 4). This is in agreement with the emission tendency reported in the Latvia's National Inventory Report (LNIR) (LNIR, 2014). However, the numerical values differ. The results depend on the choice of the database used for parameter definition, as large discrepancy exists in the data of various national databases. In addition, the choice of methodology for estimating some of the parameters might differ, thus creating the difference in the results. This is in agreement with findings of the leading forestry researchers in Latvia that conclude that diverse results are obtained when different emission calculation methods are applied (Silava, 2012).

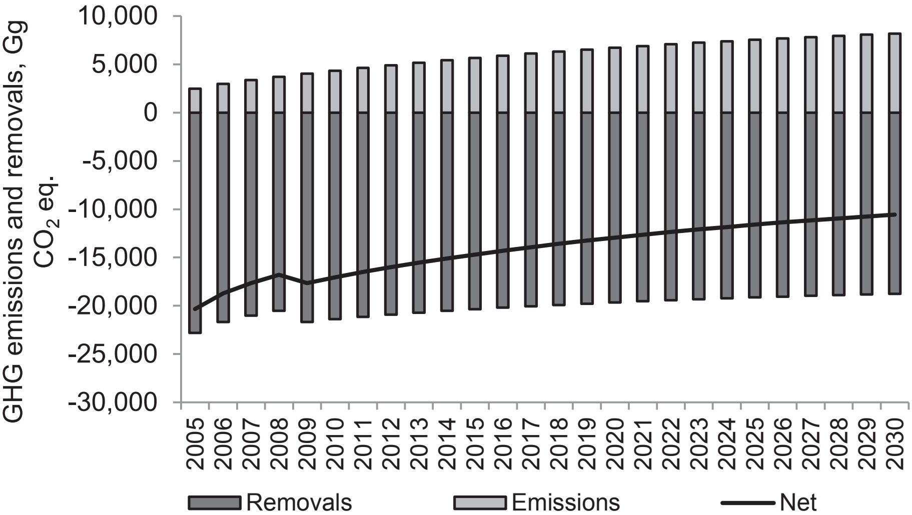

Figure 4. Results of the GHG emissions and removals in base scenario.

The results indicate that the net GHG emissions will increase as a result of the existing forestry practice (see Fig. 4). In fact, in 2030, the net GHG emissions will double. It forces reconsidering the future balance of the total national GHG emissions. Latvia has had a unique situation where all emissions generated in agricultural, energy, industrial etc. sectors were removed by the living biomass of forests. The obtained results make us conclude, that this privilege might change in the near future. Furthermore, continuation of the felling rates of the last decade will have a long-term effect, as the time necessary for trees to grow and reach the felling age takes 40 to 120 years depending on species.

The results of simulating the developed scenarios demonstrate that the largest impact on net GHG emissions would be caused by the scenario IV – considerable reduction in felling (see Fig. 5). That would cause a sharp decrease (by 34% in 2016 and 53.8% in 2030) in the net GHG emissions. As a result, in 2030, the net emissions would be 5,678 Gg CO_2 eq. less as compared to the base scenario. While the emission reduction is significant, the measure is questionable with respect to the damage caused to the forestry and wood processing industries. Reducing the felling and forest processing rates would considerably reduce the number of working places and decrease the national income from the forestry, wood processing and export of wood resources. Thus, implementation of such a limiting policy instrument would be possible only in case of proving that the gain of GHG emission reduction is larger than the economic and social loss of the industry.

Also, the results of the scenario V where an introduction of a tax was simulated demonstrate the reduced net GHG emissions. Though the emissions would decrease by 5.2% or 549 Gg CO_2 eq. the benefits should be evaluated against the impact caused on the forestry and wood processing industries. In addition, the usefulness of such an instrument should be evaluated, as the reduction in GHG emissions would be comparatively small.

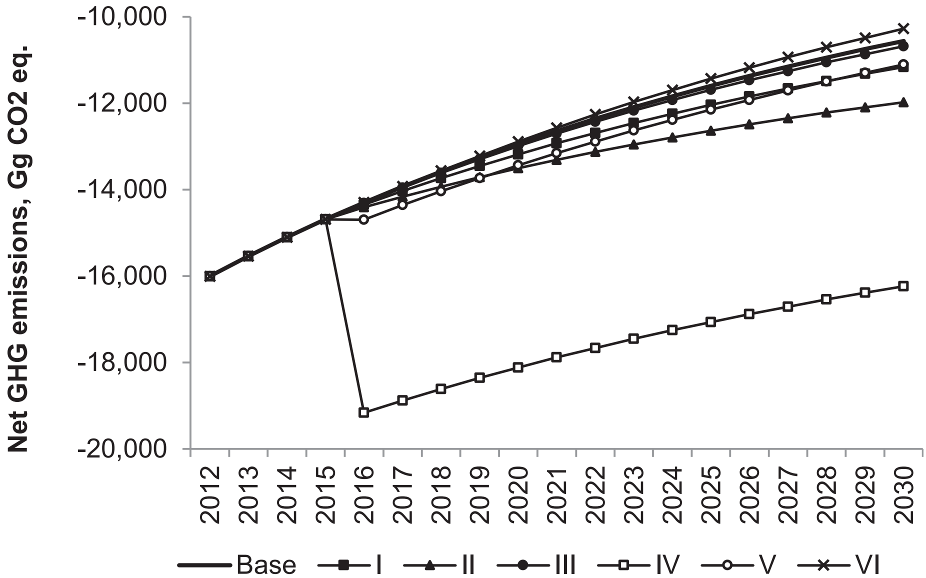

Figure 5. Results of the effects of various measures on the net GHG emission dynamics, 2012–2030.

The results of the scenarios IV and V are not reached by direct decrease of the forestry emissions, but reduction of the amount of wood processed that allows preserving the stock of the living biomass removing the emissions. The stock of living biomass has a larger impact on the total emission balance compared to the forest processing waste (see Fig. 6). The stock of stem lost in the forest processing is calculated as an immediate source of emissions, while wood processing waste left in forest would decay in a longer time, thus constantly generating small amounts of emissions. Thereof, instruments oriented towards decrease in felling rates should be implemented to achieve greater effect on the net GHG emission reduction. Still, introduction of measures reducing GHG emitted directly from the forestry sector should be considered.

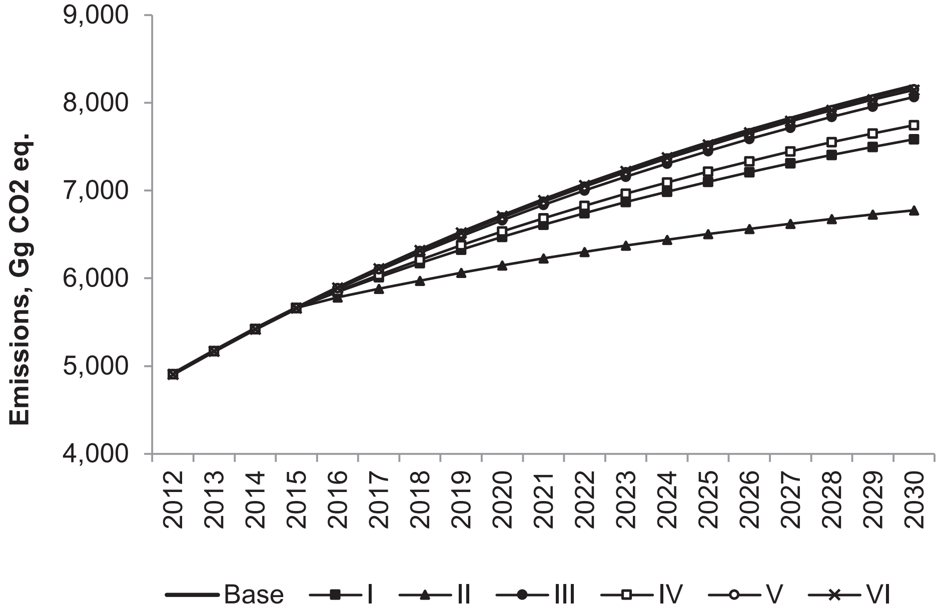

Figure 6. Results of the effects of various measures on the GHG emission dynamics, 2012–2030.

Scenarios I, II and III differed with the fraction of biomass waste used in production of products (wood chips). In scenario II, use of all technologically extractable waste was considered. Whereas, the use of the crown biomass waste only was simulated in scenario I. That way, in 2030, the emissions would be by 7.4% and 17.3% smaller in scenarios I and II, respectively, as compared to the base scenario. The least impact on GHG emission reduction would be achieved in the case of scenario III, where greenery of conifers solely would be used. In 2030, that would create emission reduction by 125 Gg CO_2 eq. or 1.5% as compared to the base scenario. While the effect on GHG emission reduction seems minor, use of conifers' greenery for manufacture of products would increase the social and economic benefits from forestry. In addition, an added value would be created for the forest processing waste turning them into a valuable resource. Moreover, use of wood processing waste would provide an option of using local renewable resources to meet the local and foreign market demand.

Reaching the target of increased fraction of the managed agricultural land will impact the forest land's emissions insignificantly (scenario VI). Comparing to the base scenario the net GHG emissions would be increased by 2.7% or 280 Gg CO_2 eq. Scenario VI is the only scenario among the simulated in our study that causes the net emissions to rise. That means that in order to reduce the emissions in the forestry sector the management of forest land and resources has to be well-considered and sustainable. Especially because options for increasing the area of forest land seem to be limited in the future.

CONCLUSIONS

A system dynamics model was developed to assess the GHG emissions from the forestry sector in Latvia. The results of the base scenario demonstrated that a tendency exists for emissions to increase and removals – to decrease. The results have confirmed that the consequence of the existing forestry practice will be an increase in the net GHG emissions that, in 2030, will reach double of the level of 2005.

Several measures that might affect the future emission generation were tested. It was found that considerable reduction (by 20%) in forest felling would reduce the net GHG emissions significantly. Yet, the implementation of such an instrument should be evaluated more thoroughly with respect to the negative economic and social effects arising from reduced activity in forestry and wood processing industries. To avoid the negative impacts on the industry, other measures that focus on the use of wood processing waste were evaluated. The results showed that it would help reducing the emissions caused by decomposition of the waste left in forests. In addition, by producing e.g. wood chips or some added-value products (as insulation materials from conifers' greenery) the forest resources would be used in a more efficient way thus providing economic and social benefits. Moreover, emission reduction in other sectors would be achieved, e.g. in energy sector by replacing the fossil fuels for wood chips.

Simulating an increase in the fraction of managed agricultural land indicated that in the future the options for increase in area of the forest land will be limited. Therefore, management of forest land and resources should be sustainable and well-considered to maintain the ability of negative net GHG emissions.

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REFERENCES

Adamovičs, A., Dubrovskis, V., Plūme, I., Jansons, Ā., Lazdiņa, D. & Lazdiņš, A. 2009. *Biomasas izmantošanas ilgtspējības kritēriju pielietošana un pasākumu izstrāde*. SIA Vides projekti, 174 pp. (in Latvian).

Berg, B. 2000. Litter decomposition and organic matter turnover in northern forest soils. *Forest Ecology and Management* **133**, 13–22.

Blumberga, A., Timma, L., Romagnoli, F. & Blumberga, D. 2015. Dynamic modelling of a collection scheme of waste portable batteries for ecological and economic sustainability. *Journal of Cleaner Production* **88**, 224–233.

Blumberga, D., Blumberga, A., Barisa, A. & Rosa, M. 2014. System Dynamic Modeling of Low Carbon Strategy in Latvia. *Energy Procedia* **61**, 2164–2167.

Bush, B., Duffy, M., Sandor, D. & Peterson, S. 2008. Using system dynamics to model the transition to biofuels in the United States. *Third International Conference on Systems of Systems Engineering*, Monterey, California, pp. 1–6. DOI:10.1109/SYSOSE.2008.4724136

CSB. 2015. Geographical Position of the Republic of Latvia. Available at: http://data.csb.gov.lv/pxweb/en/visp/visp__ikgad__geogr/GZ010.px/?rxid=a79839fe-11ba-4ecd-8cc3-4035692c5fc8.

Dace, E., Bazbauers, G., Berzina, A. & Davidsen, P.I. 2014. System dynamics model for analyzing effects of eco-design policy on packaging waste management system. *Resources, Conservation and Recycling* **87**, 175–190.

Daugavietis, M., Polis, O., Korica, A. & Seļezņovs, J. 2012. Scotch pine – a natural raw material for high-quality biologically active substances. *Proceedings of the Latvia University of Agriculture* **5**, 59–67.

Forest sector in Latvia. Available at: http://www.lvm.lv/sabiedribai/meza-apsaimniekosana/latvijas-meza-nozare.

Forrester, J.W. 1958. Industrial dynamics: a major breakthrough for decision makers. *Harvard Business Review* **36**, 37–66.

IPCC. 2006. Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). *IPCC Guidelines for National Greenhouse Gas Inventories.* IGES, Japan.

Kurz, W.A., Dymond, C.C., White, T.M., Stinson, G., Shaw, C.H., Rampley, G.J., Smyth, C., Simpson, B.N., Neilson, E.T., Trofymow, J.A., Metsaranta, J. & Apps, M.J. 2009. CBM-CFS3: A model of carbon-dynamics in forestry and land-use change implementing IPCC standards. *Ecological Modelling* **220**(4), 480–504.

LNIR, 2014. *Latvia's National Inventory Report, Submission under UNFCCC and the Kyoto Protocol, Common Reporting Formats (CRF) 1990 – 2012.* http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/8108.php

Machado, R.R., Conceição, S.V., Leite, H.G., Souza, A.L. & Wolff, E. 2013. Evaluation of forest growth and carbon stock in forestry projects by system dynamics. *Journal of Cleaner Production* (in press).

Muizniece, I., Blumberga, D. & Ansone, A. 2015. The use of coniferous greenery for heat insulation material production. *Environmental and Climate Technologies* **14** (submitted).

Muizniece, I., Lauka, D. & Blumberga, D. 2015. Thermal Conductivity of Freely Patterned Pine and Spruce Needles. *Environmental and Climate Technologies* **14** (submitted).

NDP. 2012. Cross-Sectoral Coordination Centre. *National Development Plan of Latvia for 2014–2020*.

Pollution permit. 2010. Available at: http://www.vpvb.gov.lv/lv/piesarnojums/a-b-atlaujas/?ur=vecventa&id_ur=&search_ur_submit=Mekl%C4%93t+p%C4%93c+uz%C5%86%C4%93muma.

Romagnoli, F., Barisa, A., Dzene, I., Blumberga, A. & Blumberga, D. 2014. Implementation of different policy strategies promoting the use of wood fuel in the Latvian district heating system: Impact evaluation through a system dynamic model. *Energy* **76**, 210–222.

Silava. 2008. *Celmu izstrādes tehnoloģijas enerģētiskās koksnes ražošanai.* Salaspils, 20 pp. (in Latvian).

Silava. 2012. *Latvijas meža apsaimniekošanas radītās oglskābās gāzes (CO_2) piesaistes un siltumnīcefekta gāzu (SEG) emisiju references līmeņa aprēķina modeļa izstrāde*. *Pārskats par projekta 1. etapa darbu izpildi*. Salaspils, 42 pp. (in Latvian).

State Forest Service statistics. Available at: http://www.vmd.gov.lv/valsts-meza-dienests/statiskas-lapas/publikacijas-un-statistika?nid=1047#jump.

Sterman J.D. 2000. *Business dynamics: Systems thinking and modeling for a complex world*. Irwin McGraw-Hill, Boston, 1008 pp.

Stibe, U. 1976. *Tree crown elements of quantitative indicators logging old–age spruce forest* (In Latvian). PhD thesis, Latvia University of Agriculture, Jelgava, Latvia.

The Law on Forests, Parliament of the Republic of Latvia, Latvijas Vēstnesis, 98/99 (2009/2010), 16.03.2000., 'Ziņotājs', 8, 20.04.2000.