DYNAMICS OF ENERGY WOOD QUALITY DURING LONG-TERM STORAGE IN WOOD PILES IN LATVIA

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Abstract. The aim of this study was to evaluate the dynamics of dry matter losses in energy wood during long-term storage in Latvia, taking into account storage duration, season, regional climatic differences, and the dominant tree group. The Yasso20 organic matter decomposition model, based on five biochemical fractions (AWENH), was used to predict the decomposition of logging residues. The model integrates 10-year average monthly meteorological data for Latvian regions and includes an approach that enables the effect of the storage start month on decomposition intensity to be assessed. The results showed that dry matter losses increased non-linearly and, in the base scenario, reached 4.23% after 6 months, 12.33% after 12 months, 22.89% after 24 months, and 31.11% after 36 months. In short-term storage, the extraction season was significant: the lowest losses were predicted for storage initiated in autumn, whereas the highest losses were predicted for spring. Over longer periods, the effect of the initial season gradually levelled out, and the overall climatic effect became dominant. The results confirm that storing energy wood in the forest is useful mainly in the short and medium term, whereas prolonged storage causes substantial dry matter losses and reduces resource-use efficiency.

Keywords: energy wood, dry matter losses, storage, Yasso20.

Introduction

Storage of energy wood in the forest after extraction is an important stage in the biofuel supply chain because it affects not only logistics, but also fuel quality, energy density, and the overall efficiency of resource use. Previous studies in the Nordic countries and the Baltic region show that roadside storage in piles is not a passive process: material drying, rewetting, dry matter losses, and biochemical changes occur simultaneously, jointly determining whether storage improves or reduces energy wood quality. Previous research has concluded, for example, that the positive effect of storage dominates in the initial stage through moisture reduction; however, as storage duration increases, dry matter and energy losses become increasingly significant [1-3].

Among all quality indicators, moisture content is the most important because it directly affects the net calorific value, transport costs, and the suitability of the fuel for further processing and energy generation. Studies on logging residues have shown that fresh material can dry very rapidly during the warm season. Nurmi [4] found that storage in small heaps on the clear-cut site ensured better drying than roadside piles, and the average moisture content on the site decreased to 28.5%, whereas in roadside piles it was 42.2%. Similarly [5] showed that freshly produced logging residues in May could reduce moisture content to approximately 28.6% within three weeks. Nurmi and Hillebrand [10] also concluded that 2–3 weeks of pre-storage on the clear-cut site in early summer may reduce moisture content by up to about 30%, substantially improving chipping and transport efficiency later on.

However, the literature just as clearly emphasizes that the favourable drying effect is not unlimited. Energy wood is a hygroscopic material; therefore, after the summer drying period, rewetting occurs under the autumn and winter conditions. The IEA Bioenergy review [3] indicates that logging residues can regain a considerable share of previously lost moisture in autumn, especially in uncovered piles. The same trend is confirmed by the most recent Latvian study, which found that the moisture content of energy wood decreased to 33.57% in summer, but increased to 42.20% in the autumn and reached 49.52% in winter, clearly indicating seasonal deterioration in quality during longer storage periods [6].

The outcome of energy wood storage largely depends on the biomass form. Uncomminuted logging residues, small-dimension material such as branches and bundled material usually store more stably than freshly produced wood chips. Jirjis [1] emphasized that chipping before storage increases the material surface area and promotes biological activity. Filbakk et al. [2] also concluded that, in order to optimize the use of logging residues for energy, it is important to assess how different storage and processing methods affect both moisture content and dry matter losses. IEA Bioenergy summarizes this even more directly: uncomminuted biomass in open-air drying generally loses moisture gradually and with a lower risk of degradation, whereas chip piles are more prone to self-heating, microbial decomposition, and energy losses.

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The main limiting factor in long-term storage is dry matter loss. These losses result from fungal development, microbial decomposition, and mechanical losses. Therefore, storage efficiency cannot be assessed solely on the basis of moisture reduction or an increase in the calorific value on a dry matter basis. From a practical perspective, the key question is how much of the dry matter and energy initially brought into the pile is retained until the time of use. The IEA Bioenergy review [3], drawing on several earlier studies, indicates that dry matter losses during storage of logging residues often reach 1–3% per month. Filbakk et al. [2] found in a modelling study that dry matter losses within this range are also characteristic of Northern European conditions, and that residues from spruce stands showed more pronounced losses than material prepared from pine stands. Thus, in long-term storage, quality assessment must simultaneously consider moisture content, dry matter mass, and available energy, rather than any single indicator in isolation.

A particularly important study for the Baltic region is the Estonian research on extra long-term storage of logging residues. Padari et al. [7] analysed covered and uncovered piles of birch and spruce logging residues over a multi-year period. The study showed that fuel quality in covered piles changed relatively slowly during the first two years, but that degradation accelerated later. The authors concluded that excessively long storage is not recommended because, although some quality indicators may still remain acceptable, overall energy density and the amount of retained energy decrease. Padari et al. [7] reported earlier findings showing that, over seven months, the decline in energy content of spruce logging residues was 0.6% in a covered pile and 5.3% in an uncovered pile, clearly demonstrating the importance of covering.

Pile construction, contact with the ground, and covering also play an important role in long-term storage. In a study on controlling the moisture content of logging residue piles, Eliasson et al. [8] concluded that the only approach that consistently provided drier fuel than an uncovered pile was the use of a biomass cover both below and above the pile, thereby reducing direct contact with wet ground and rewetting from precipitation. Similar conclusions are summarized in the IEA Bioenergy review [3], which states that covering can reduce the moisture content by an additional 3-6 percentage points compared with uncovered material. This means that the success of long-term storage depends not only on the storage duration as such, but also on the quality of the pile construction and site selection.

Ash content and net calorific value on a dry matter basis usually change less during storage than moisture content or dry matter mass; however, these indicators are also important. Kaleja et al. [6] showed that under Latvian conditions, the net calorific value increases as moisture content decreases, but ash content may fluctuate during storage and may increase in certain periods. This may be related to possible contamination by mineral particles, an increase in the share of fine fractions, or differences in material composition. Therefore, from a practical point of view, fuel quality must be assessed comprehensively: even if the calorific value on a dry matter basis increases slightly, this does not mean that long-term storage is advantageous overall, because dry matter losses may reduce the total usable energy.

Based on the literature reviewed above, storage of energy wood in the forest after extraction is effective only within a certain time window. During the warm season, storage usually improves the fuel quality because moisture decreases and net calorific value increases, but as storage duration increases, dry matter, energy, and quality losses become increasingly pronounced. Overall, the literature supports the approach that logging residues and other energy wood should be stored after extraction in an uncomminuted form, in well-ventilated and preferably covered piles, taking advantage of natural drying during spring and summer while avoiding excessively long storage periods of several years. Consequently, the central research question under Latvian conditions is not whether storage is necessary, but rather what the optimal storage duration is, and under which conditions the benefits of moisture reduction still outweigh dry matter and energy losses.

Materials and methods

This study assessed dry matter losses of energy wood during long-term storage under Latvian conditions using the Yasso20-based calculation tool adapted for logging residue piles in Latvia. The approach is based on the Yasso20 model [9] and was applied to estimate changes in biomass mass over time as affected by storage duration, start month of storage, region, and dominant tree group. Since

Yasso20 is an established model, its full equation system is not repeated here; only the methodological steps relevant to this application are described.

Yasso20 describes organic matter decomposition through a set of chemically defined compound groups and climate-dependent decomposition rates. In this study, the model was used to simulate the decomposition of logging residues and energy wood during storage by applying monthly climate data and biomass composition parameters representative of Latvian conditions. The model outputs were further converted into practically interpretable indicators, namely relative dry matter loss (%) and the remaining wood-chip loose cubic meters (bulk m³) after a defined storage period.

The simulations were based on regional monthly climate datasets representing the main forest regions of Latvia. The model used average monthly air temperature and precipitation as climatic input variables. To reduce the influence of single-year anomalies, the datasets were compiled as 10-year regional averages (Table 1). Consequently, the results were interpreted as responses to differing climatic conditions represented by the regional datasets rather than to the administrative regions themselves.

Table 1

Mean annual air temperature and annual precipitation of the regional climate datasets used in the simulations

Climate dataset	Mean annual air temperature, °C	Annual precipitation, mm
Zemgale	7.71	688
Latgale	6.43	640
Vidzeme	6.43	640
Kurzeme	7.73	700
Pierīga	7.23	675

The study analysed two biomass groups: coniferous energy wood and deciduous energy wood, represented by logging residues intended for fuel production.

The initial amount of stored biomass was standardised to 1000 bulk m³ in the base scenario in order to ensure comparability among storage durations and start months.

The model was applied to simulate storage periods of 1 to 36 months. In order to assess the effect of storage season, simulations were repeated for all twelve possible start months. This made it possible to evaluate how the timing of extraction and storage initiation affects dry matter losses in short-, medium-, and long-term storage. In addition, simulations were compared among Latvian regions and between coniferous and deciduous biomass in order to evaluate the influence of climatic and compositional differences.

Dry matter loss was calculated as the relative reduction in biomass mass during storage (1).

$$L = \frac{M_0 - M_t}{M_0} * 100, \tag{1}$$

where L – dry matter loss, %;
M_0 – initial biomass at the start of storage;
M_t – remaining biomass after storage time.

To express the model results in a practically applicable form, the remaining biomass was converted to the corresponding amount of wood chips in bulk volume units (2).

$$V_t = V_0 * (1 - \frac{L}{100}), \tag{2}$$

where L – dry matter loss, %;
V_t – remaining wood-chip volume after storage, bulk m^3;
V_0 – initial wood-chip volume, bulk m^3.

To evaluate the effect of the storage season, the monthly climate sequence used in the model was shifted according to the selected storage start month. Thus, each scenario began with the climatic conditions corresponding to the actual month of extraction, followed by the subsequent monthly sequence over the selected storage duration. This approach allowed assessment of the sensitivity of dry matter loss to the timing of storage initiation.

To characterise the variability of predicted dry matter losses, minimum, average, and maximum values were analysed for the main storage durations. These ranges reflect uncertainty related to climatic variability and conversion of modelled biomass losses into practically interpretable output indicators.

The model results were summarised by storage duration, start month, region, and tree group. The main output variables used in result interpretation were:

- dry matter loss, **%**;
- remaining biomass amount;
- remaining wood-chip bulk volume, bulk m³.

To assess the effect of storage duration on modelled dry matter losses, the results for 6, 12, 24, and 36 months were compared across the 12 simulated storage start months using the Friedman test. Pairwise differences between storage durations were further evaluated using the Wilcoxon signed-rank test.

Results and discussion

The Yasso20 modelling results showed that energy wood losses during storage increase non-linearly and are substantially affected by both the storage duration and the season when storage begins. In addition to the storage duration and start season, the modelling results also showed the influence of regional climatic conditions and biomass composition on dry matter losses. In the base scenario (Vidzeme, coniferous biomass, extraction in December, initial volume 1000 bulk m³), losses after 6, 12, 24, and 36 months reached 4.23%, 12.33%, 22.89%, and 31.11%, respectively (Table 2). This corresponds to a projected reduction in chip volume to 957.7, 876.7, 771.1, and 688.9 bulk m³. The results indicate that substantial resource losses occur already within the first year, whereas longer storage causes a rapid cumulative reduction in mass.

Table 2

Modelled material losses and resulting wood chip volume at different storage durations

Storage duration, months	Losses, avg.%	Losses, min.%	Losses, max.%	Resulting wood chip volume, bulk m³	Uncertainty range, bulk m³
1	0.04	0.02	0.08	999.6	999-1000
3	0.23	0.10	0.46	997.7	995-999
6	4.23	2.00	7.74	957.7	923-980
12	12.33	6.72	19.99	876.7	800-933
24	22.89	13.29	35.02	771.1	650-867
36	31.11	18.80	45.82	688.9	542-812

The storage start month significantly affected the results in the shorter term. After 6 months of storage, the lowest losses were predicted when extraction took place in September or October (1.11-1.13%), whereas the highest losses were observed in March and April (10.53-10.58%) (Table 3). This indicates that the seasonal influence is decisive in short-term storage, because the material stored in autumn is initially exposed to cooler conditions, whereas the biomass extracted in spring quickly enters the warm season, when decomposition intensity increases. At the same time, after 12, 24, and 36 months, the differences between the start months became minimal, indicating that, in the long term, the effect of the initial season levels out. A statistical comparison of the simulated dry matter losses showed a significant effect of storage duration across the 12 storage start months (Friedman test, $p < 0.001$). Pairwise comparisons indicated significant differences between all analysed storage durations (Wilcoxon signed-rank test, $p < 0.001$), confirming that dry matter losses increased consistently with the storage time.

After 36 months, the lowest losses were obtained under the climatic conditions represented by Vidzeme and Latgale (31.11%), whereas the highest losses were observed under the climatic conditions represented by Zemgale (34.74%), followed by Kurzeme (33.74%) and Pierīga (33.06%). This confirms that differences in climatic conditions affect long-term decomposition intensity, although the regional differences are not very large. In addition, broadleaved biomass decomposed slightly faster in the model than coniferous biomass, indicating the importance of biomass composition in the evaluation of long-term storage.

Table 3

Changes in losses depending on the extraction month at different storage durations

Extraction month	Losses after 6 months, %	Losses after 12 months, %	Losses after 24 months, %	Losses after 36 months, %
Jan	7.06	12.32	22.88	31.11
Feb	9.4	12.32	22.88	31.1
Mar	10.58	12.31	22.87	31.09
Apr	10.53	12.3	22.84	31.06
May	9.43	12.29	22.83	31.04
Jun	7.44	12.3	22.85	31.07
Jul	4.65	12.34	22.91	31.15
Aug	2.15	12.36	22.95	31.19
Sep	1.11	12.35	22.94	31.17
Oct	1.13	12.34	22.91	31.14
Nov	2.09	12.33	22.9	31.12
Dec	4.23	12.33	22.89	31.11

Uncertainty analysis showed that the spread of projections increases with the storage duration, reflecting the combined effect of the climatic scenario variation and conversion uncertainty from modelled biomass losses to wood-chip bulk volume. In the base scenario, after 36 months the loss range reached 18.80-45.82%, indicating a substantial influence of climate and conversion uncertainty. However, even in the most conservative scenarios, losses remained high during long-term storage.

The obtained results are consistent with previous studies emphasizing that storage may initially improve fuel quality due to moisture reduction, but over longer periods dry matter and energy losses begin to dominate. Therefore, storage of energy wood in the forest after extraction should be regarded as useful mainly in the short and medium term. Combining the modelling results with the moisture dynamics described in the literature, it can be concluded that under Latvian conditions the optimal storage period most likely does not exceed 6-12 months.

It should be noted that the modelling approach primarily reflects dry matter losses caused by organic matter decomposition and does not fully include all practical storage features, such as pile geometry, cover type, and local moisture differences. Therefore, the results should be interpreted as a scientifically grounded estimate of losses rather than a universally applicable absolute forecast for all storage situations.

Conclusions

1. Dry matter losses increase with storage duration and become significant after the first year. The modelling results showed that losses in the base scenario increased from 4.23% after 6 months to 12.33% after 12 months, 22.89% after 24 months, and 31.11% after 36 months. This indicates that long-term storage substantially reduces the amount of retained biomass.
2. The storage start season significantly affects losses in the short term, but this effect levels out in the long term. After 6 months, losses differed considerably depending on the extraction month: the lowest losses were observed when storage started in the autumn, whereas the highest were observed in spring. In contrast, after 12-36 months, differences between the start months became minimal, as the cumulative climatic effect became dominant.
3. The optimal storage period is most likely limited to 6-12 months, because after that dry matter losses begin to exceed the potential benefits of drying. Although moisture reduction during the initial stage of storage may improve fuel quality, in prolonged storage dry matter and, consequently,

energy losses become increasingly large. Therefore, storage over several years should not be considered an efficient solution.

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Author contributions

Conceptualization, A.Z.; methodology, A.Z. and S.K.; investigation, A.Z., S.K. and J.C.; data curation, A.Z.; writing – review and editing, A.Z. All authors have read and agreed to the published version of the manuscript.

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