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How Climate Change Will Affect Forest Composition and Forest Operations in Baden-Württemberg—A GIS-Based Case Study Approach

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Abstract: In order to accommodate foreseen climate change in European forests, the following are recommended: (i) to increase the number of tree species and the structural diversity; (ii) to replace unsuitable species by native broadleaved tree species, and (iii) to apply close-to-nature silviculture. The state forest department of Baden-Württemberg (BW) currently follows the concept of Forest Development Types (FDTs). However, future climatic conditions will have an impact on these types of forest as well as timber harvesting operations. This Geographic Information System (GIS)-based analysis identified appropriate locations for main FDTs and timber harvesting and extraction methods through the use of species suitability maps, topography, and soil sensitivity data. Based on our findings, the most common FDT in the state forest of BW is expected to be coniferous-beech mixed forests with 29.0% of the total forest area, followed by beech-coniferous (20.5%) and beech-broadleaved (15.4%) mixed forests. Where access for fully mechanized systems is not possible, the main harvesting and extraction methods would be motor manual felling and cable yarding (29.1%). High proportions of large dimensioned trees will require timber extraction using forestry tractors, and these will need to be operated from tractor roads on sensitive soils (23.0%), and from skid trails on insensitive soils (18.4%).

Keywords: forest operations; timber harvesting; timber extraction; forest development types; species suitability map

1. Introduction

Since the beginning of the 20th century, anthropogenic greenhouse gas (GHG) emissions [1] have caused a steady rise in the mean annual temperature around the world. In Germany, the reported increase from 1881 to 2014 was 1.3 °C [2]. Besides the temperature increase, climatic simulations for Central Europe show changes in precipitation regime. While the annual precipitation may remain constant, both higher rainfall intensity [3] and more frequent droughts [4] are expected. Given the current climate change projections, diverse impacts are to be anticipated for forests, such as a northward shift of several hundred kilometers for single tree habitats [5], an altitudinal shift of 300 to 400 m [6], extended vegetation periods [7], and changes in biomass increments [8].

To improve resistance and resilience of forests to climate change, it is generally agreed that both the number of species and the structural diversity of forests should be increased [9]. Resistance and stability refers to the capacity of a system to absorb disturbances and to forestall impacts [10–12], whereas resilience is the capacity to recover and to return to the equilibrium or pre-condition state after a disturbance/perturbation [11,13,14]. Nevertheless, a major issue in forest management planning is the prediction of future forest conditions, and identification of species suitable to these future conditions. This is why projections of species distributions under both climatic and global environmental change are of great scientific and societal relevance [15]. Different approaches have been developed to identify the most suitable tree species and management strategies. These include bioclimate envelopes [16], spatio-temporal site-index predictions [7] or species distribution models [17,18]. As they are mainly focused on the suitability of individual tree species to expected future environments, they can model one species at a time in order to map its future spatial range [19]. Bolte et al. (2009) [20] mention the possibility of integrating these analyses into silvicultural concepts of forest dynamics, e.g., the Forest Development Type (FDT) approach.

The concept of FDTs was developed decades ago as a strategic approach for: (i) illustrating long-term goals for forest development in a given locality and; (ii) describing the transition of existing forest stand types into types that are well adapted to moderate climate change [21,22].

The importance of the concepts of close-to-nature or continuous-cover forestry is widely accepted [23]. Management strategies are increasingly focused on the diversification of vertical and horizontal forest structures, including a greater diversity of tree species [4]. The implementation of FDTs in Germany [24–26] follows this principle of favoring site-adapted broadleaved species. Results of the third national forest inventory showed a 7% increase in the area of broadleaved trees from 2002 to 2012, with the area increasing from 4,317,236 ha to 4,632,637 ha [27]. Increases in the area covered by broadleaved trees are also reported in Baden-Württemberg (BW). BW is a Federal state in southern Germany with forests typical for Central European conditions due to a large variation in altitudes, sites conditions, silvicultural management approaches, and stands with mixtures of broadleaved and softwood species [28]. At the moment, the most predominant tree species in BW is Norway spruce (*Picea abies* H. Karst), which covers 33.5% of the total forested land base. European beech (*Fagus sylvatica* L.) is the most common broadleaved species, covering 21.5% of the forested area [29], and it is the naturally dominant tree species [18]. Because climate change is expected to progress faster than forests can adapt [30], forest management has a particular focus on these two main tree species. The state forestry department of BW (Forst BW) intended to increase the ratio of broadleaved trees, particularly by replacing unsuitable Norway spruces with native European beeches, oaks (*Quercus robur* L. and *Quercus petraea* Liebl.), silver firs (*Abies alba* Mill.) and additional broadleaved tree species [31].

As a consequence of the tree species shift, an increase of mixed stands with high structural varieties and changing precipitation regime, changes in the degree of mechanization of felling operations will likely occur. Given the preference for motor-manual systems (chainsaws) in beech stands, this kind of operation may likely gain in popularity at the expense of single grip harvesters—which are typical in coniferous stands—in fully mechanized systems. Moreover, a greater diversity of structures in forests may favor management regimes based on natural regeneration, single-tree harvest, habitat-adapted tree species and provenances [4,32].

In addition to the altered tree species composition, future climatic conditions in BW will create additional constraints on timber harvesting operations. On frozen ground, skidders work more efficiently and cause less damage due to increased bearing capacity [33]. Because the mean annual temperature is rising, the number of days with frozen ground during the traditional logging period in winter is expected to decrease [34,35]. Moreover, the expected 35% increase in precipitation in the winter season in BW [36] will likely result in higher soil moisture content and wetter soil conditions. It is highly probable that soil moisture and the water balance will remain high during winter [37], which is not favorable to any ground-based forest operation [38]. Increased rutting, higher soil bulk densities, and lateral soil displacement are to be expected with winter operations.

In spite of all these additional constraints, it can be assumed that harvesting will still be carried out mostly during the winter season because of the increasing proportion of broadleaved trees, nature conservation aspects and work safety. Therefore, innovative timber harvesting and extraction operations that minimize soil damage caused by modern technical equipment (e.g., weight, number of axles and wheels), as well as appropriate harvesting and extraction methods (e.g., cable, horse, tethering winches) [5], need to be applied.

The key question addressed in this study is how climate change will affect future timber harvesting operations. More specifically, the research objectives were to identify, quantify and interpret expected qualitative changes in forests in BW due to climatic change ("How will future forests look?"); to describe those forest types that will potentially be the most relevant FDTs in BW; and to identify forest harvesting operations that are most adapted to expected future conditions in these FDTs.

2. Material and Methods

2.1. Concept, Tools and Data

The study partly relied on a Geographic Information System (GIS) (2015 ESRI® ArcGIS 10.3.1). Using a GIS to represent the most relevant FDTs and terrain data relevant for forest operations seemed to be the most adequate approach because (i) most site-relevant data were available in digital format, and (ii) restrictions and/or site-specific characteristics could be incorporated. This approach, which consists of combining different GIS layers with specific information, has previously been applied: to determine suitable areas for short rotation coppices [39,40]; to assess biomass potentials [41–45]; and to select appropriate timber harvesting systems [46,47]. Information about soil type, terrain slope, and stand composition as well as species suitability maps, which already include climate and site quality data, were provided by the BW Forest Research Institute (FVA BW) [48]. Additionally, data regarding soil sensitivity to traffic were also available for map units called regional site units [49] in a Microsoft Access file (2013 Microsoft ® Access ® 15.0.4857.1000) [48]. These data on the regional site units were imported into GIS. All input data were collected by forestry departments in 2010 [49], and were compiled by regional authorities and FVA BW to ensure that all data collected in BW were reported in the same format and at the same level of detail.

2.2. Species Suitability Data

The collection of data on the suitability of tree species in BW started in the 1970s [50], but the resulting "maps were originally based on expert knowledge of the site classification" [18]. The current species suitability predictions, provided by the FVA BW [48], were based on a statistical model which predicted the presence or absence of a tree species under given climatic conditions. The statistical approach is described by Hanewinkel et al. [18]. The original "presence/absence information per species [was] derived from the 'Data on Crown Condition of the systematic grid (16 × 16 km)' (Level I) from the 'International Co-operative Programme on Assessment and Monitoring of Air Pollution on Forests'" [18]. The presence/absence data were coupled with site-specific tree physiology values (mostly based on temperature and precipitation) before being statistically analyzed to identify correlations [51]. Thirty-arc-second tiles were used as spatial resolution for climate data [18]. In order to predict the species suitability to future climatic conditions, the values of explanatory variables were changed to match expected climates for the year 2050. The mean annual temperature was increased by about 2 °C, whereas the mean annual precipitation was decreased by 25 mm, mainly during the vegetation period [31]. The model generated maps of predicted probabilities of observed species. In a further step, detailed site classification information was analyzed by experts in order to provide information about the following attributes of the species [50,51]:

1. Competition strength
2. Soil protection
3. Growth performance
4. Stability

With these four attributes, the FVA BW generated a database that contained the potential of different tree species to grow under climatic conditions predicted for 2050 in each of the 5023 regional-site units. The tree suitability map had a resolution of 1:50,000 [51].

Each attribute was assigned a value on the scale from best to poorest, representing the suitability of tree species. 'Competition strength' took into account both the regeneration and the competitiveness of mature trees. 'Soil protection' considered the impact of the species on both humus and soil (e.g., the root depth). 'Stability' included biotic and abiotic dangers, and finally, 'growth performance' reflected the volume growth or market value [48].

Based on the ranking of the four attributes, an overall assessment of tree species suitability for each regional-zonal site unit was expressed using a six-category classification, with classes ranging from biologically important to inappropriate. In this study we focused on the site units that were ranked as 'biologically important', 'very suitable', 'suitable', and 'possible growth', since they represented the tree species suitable to future climatic conditions. On specific sites, some tree species were considered biologically important for humus formation, soil protection or for protective forests [48], and were therefore assessed manually. The decision matrix for assessing tree species suitability showed 135 possible combinations between the different values of the four above-mentioned attributes (Table 1). The matrix with all possible combinations for the tree species suitability classes 'very suitable', 'suitable', and 'possible growth' is shown in Table 1. For the sake of simplicity, we did not show the combinations that would lead to determining unsuitable tree species [52].

Table 1. Matrix for the assessment of tree species suitability for the classes 'very suitable', 'suitable', and 'possible growth'. The attributes 'competition strength', 'soil protection', and 'performance' are assigned values from best (1) to poorest (3), and the attribute 'stability' from best (1) to poorest (5) [52]. As an example of how the matrix works, we enclose one possible combination in red. It shows that a tree species is considered as suitable on a regional-zonal unit when the competition strength is assigned a value of 2, soil protection a value of 3, and stability and performance with values of 1 respectively.

Very suitable	Competition strength	1	2	3	1	2	1	1												
	Soil protection	1	1	1	2	2	1	1												
	Stability	1	1	1	1	1	1	2												
	Performance	1	1	1	1	1	2	1												
Suitable	Competition strength	3	1	2	2	1	1	2	3	1	2	1	1	1						
	Soil protection	2	3	3	1	2	1	1	1	2	2	3	1	1						
	Stability	1	1	1	1	1	1	2	2	2	2	2	2	3						
	Performance	1	1	1	2	2	3	1	1	1	1	1	2	1						
Possible growth	Competition strength	3	3	2	1	1	1	3	2	2	1	1	2	3	1	1	1	1	1	1
	Soil protection	3	1	2	3	2	3	2	3	1	2	3	1	1	2	3	1	1	2	2
	Stability	1	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3	4	4	2
	Performance	1	2	2	2	3	3	1	1	2	2	2	1	1	1	1	2	1	1	3

2.3. Derivation of FDTs from Species Suitability Data

The concept of FDTs is currently in use in several federal states of Germany and Denmark [22,25,26,53]. It is applied in the state forests of BW, and supported by guidelines which describe 17 FDTs [24]. For a given set of climatic and stand conditions, the FDT description includes information about species distribution, rotation length, regeneration dynamics, forest management activities (tending, thinning and final cutting [28]) and timber assortments [54]. This study focused on six particular FDTs, which are described in Section 2.4. The FDTs were selected according to their current and predicted tree species: Norway spruce, beech, silver fir and oak. Altogether, these six FDTs covered 82% of the analyzed 379,215 ha forests managed by Forst BW. These public forests represented 27.6% of the forest area in BW. The area of the dataset is 424,160 ha, from which 44,945 ha were unsuitable for this study, as information was missing. The spatial extent and location of the study area is shown together with the total forest area of BW in Figure 1 [55], because for the interpretation the relevance of FDT in different areas, the remaining forest area is important. The main tree species in the state forest of BW are spruce (32.6%), beech (24.6%), silver fir (8.3%) and oaks (6.5%) [56]. This differs slightly from the overall composition of all forests in BW.

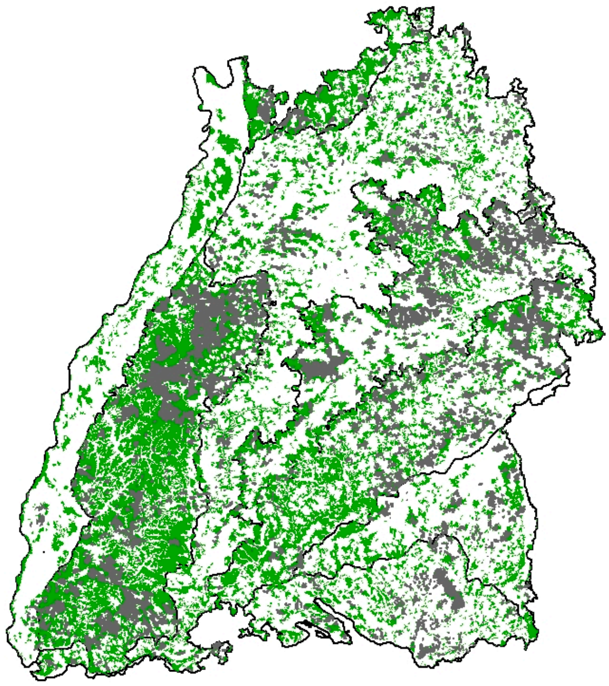

Figure 1. Spatial extent and location of the analyzed area (in grey) in comparison to whole Baden-Württemberg (BW) forest (in green) with the natural regions of third level (black lines), adapted from [55].

We followed the same assumptions as those outlined in Witt et al., Forst BW and Saar Forst [21,24,57] about the shares of species. Very suitable sites were assumed to allow the growth of a dominant tree species, meaning that the dominant tree species on these sites accounted for more than 50% of the area. The class 'possible growth' indicated that a tree species could reach proportions of between 20% and 50% of the area composition, and therefore represented an important associated species.

In addition to the species suitability, we favored conifers over broadleaved tree species on sites where both were ranked suitable. Conifers represent more than 66% of the total harvest in BW [58] and annual incomes from coniferous forests are around 100 €/ha higher than those from broadleaved forests [59]. Given the economic importance of coniferous species, it seemed reasonable to assume that forest managers would have a preference for these species whenever they are suitable. The resulting derivation of future FDTs on the tree species suitability data is represented in Figure 2.

2.4. Forest Development Types

Coniferous-beech-mixed forests (FDT1)

FDT 1 contains silver fir covering up to 60% of the total forest area. However, spruce and Douglas fir (*Pseudotsuga menziesii* Franco) may also make up high proportions on specific and suitable sites. Overall, the proportion (by area) of the dominant coniferous tree species is 50–80%, while the proportion of beech ranges between 10 and 50% [21]. Other suitable broadleaved tree species are sycamore maple (*Acer pseudoplatanus* L.), European hornbeam (*Carpinus betulus* L.), and ash (*Fraxinus excelsior* L.). Between 30–50% of the whole merchantable biomass comes from diameters of large dimension, with a diameter at breast height (DBH) greater than 50 cm [24].

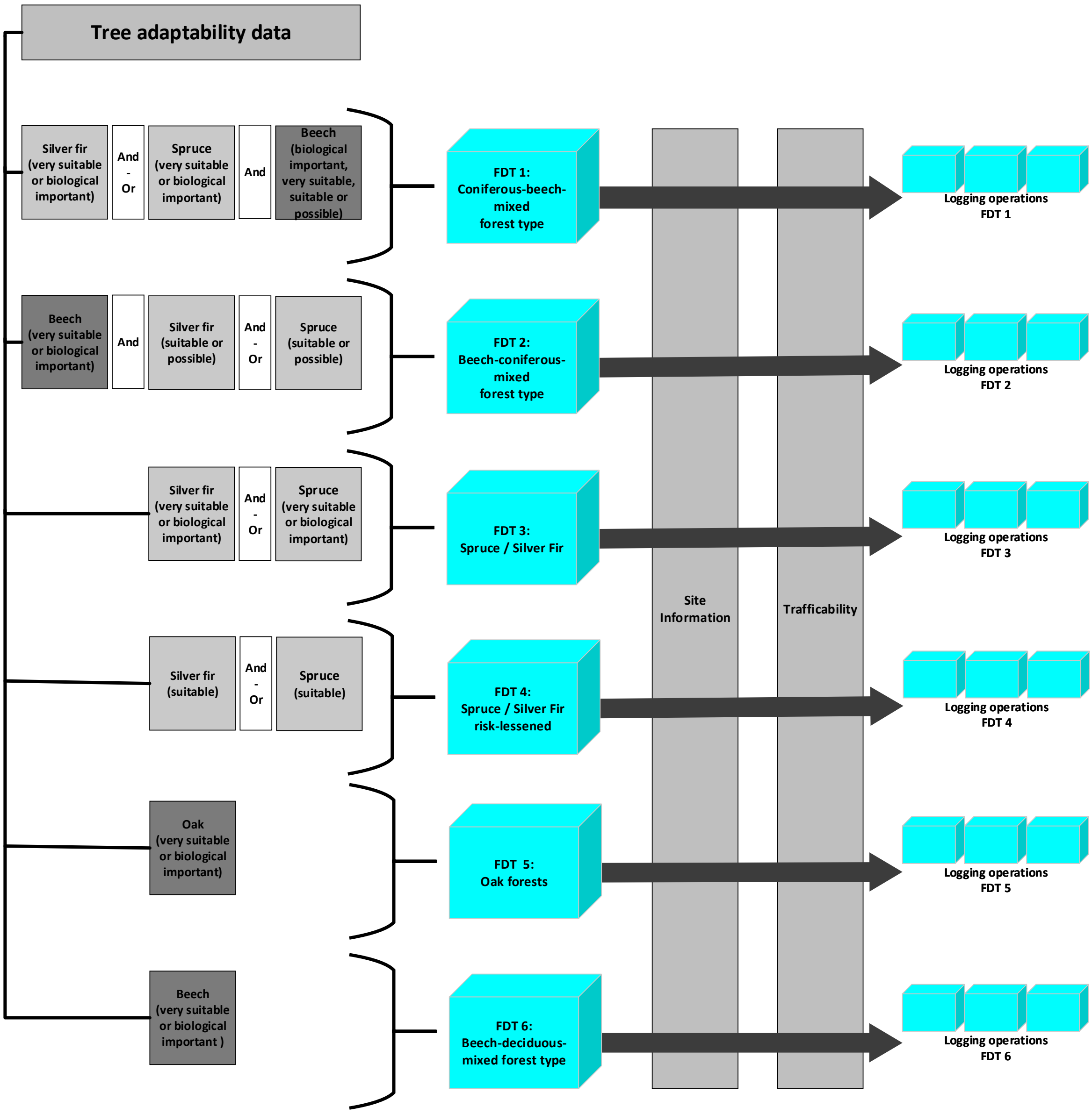

Figure 2. Flowchart of the Geographic Information System (GIS) analysis to determine Forest Development Types (FDTs) from species suitability data and timber harvesting and extraction operations from site information and trafficability data.

Beech-coniferous-mixed forests (FDT 2)

Beech-coniferous-mixed forests are dominated by beech trees (40–80% of the total area) and mixed with coniferous trees—mostly spruce or pine (*Pinus sylvestris* L.)—covering up to 40% of the total area [24,57]. In this FDT, beech is always the dominant tree species and the production goal is high quality beech timber of large dimension (DBH of 60 cm). Lower quality trees and conifers are harvested at DBH of 50 cm [24].

Reduced risk spruce forests (FDT 3)

In this FDT, the rotation lengths would be reduced to 40–60 years, during which DBHs of 40 cm can be reached [60]. The reduction of rotation length may help to limit damage by some of today's most prominent forest issues, e.g., windthrow, cambium-feeding insects, and root rot [61]. Under this new management strategy, this type of forest is expected to produce high quantities of wood for material usage, mostly lumber, because the proportion (by area) of coniferous tree species (mostly spruces), at 60–80%, is very high [24].

Silver fir forests (FDT 4)

This FDT targets high proportions of coniferous species with mainly silver fir and spruce. Commonly, wood production is oriented towards large diameters (DBH 50–80 cm) [24]. Mixture with beech is common, but beech is not dominant. Particularly when single tree selection systems—also known as Plenterwald [62]—are applied, the proportion (by area) of beech never exceeds 20% [24,57].

Oak-mixed forests (FDT 5)

Common oak and sessile oak forest types are grouped into this oak-mixed forest type. The proportion of oak species is high (at 60–90% of the total area in mixed forests) [24].

Beech-broadleaved-mixed forests (FDT 6)

This FDT has beech proportions (40–80% of the total area) similar to those of the beech-coniferous-mixed forests (FDT2). In addition to beech, sycamore maple, cherry (*Prunus avium* L.), oak and ash are the most predominant species on the sites. Coniferous tree species can be found as an admixture, representing up to 20% of the total area [24,57].

By combining the different layers of species suitability, topography and site sensitivity, it was also possible to prescribe optimal logging operations to the FDTs (Figure 2). Moreover, it was possible to assign a FDT to each site unit under the climatic conditions predicted for 2050.

2.5. Timber Harvesting and Extraction Systems

2.5.1. Soil Sensitivity

Technical terrain classification is based on three criteria: terrain slope, ground condition (bearing capacity), and ground roughness (microtopography). In our study, we focused on assessing terrain slope and soil sensitivity based on ground conditions, since microtopography data were not available for the whole study area.

Soil compaction and displacement are important aspects in forest operations [63–65]. Soil sensitivity represents the risk of irreversible soil disturbance due to machine traffic. Irreversible soil disturbances should be avoided in order to secure all the natural processes that occur in the soil, which ensure a preservation of forest ecosystems and maintain optimal productive functions in forests [66]. Our analysis was based on the soil texture for each regional site unit in the Microsoft Access file grouped into classes (Table 2) which were integrated as GIS-layers. The varying vulnerability of different soils to traffic was already classified by Wiebel [49], who grouped different soil textures into the classes (i) sensitive; (ii) insensitive, and (iii) partly sensitive [48] (Table 2).

Table 2. Risk of soil disturbance from machine traffic according to soil texture, adapted from Wiebel [49], where "−" indicates that soils are insensitive to traffic; "+" indicates that soils are sensitive to traffic; and "+/−" indicates that soils are partly sensitive to traffic.

Soil Texture	Sensitivity
Clayey	+
Loamy-clayey	+/−
Silty-loamy + clayey	+
Silty-loamy	+
Loamy	+
Loamy; sandy	+/−
Gravelly	−
Rocks	−
Varied; diverse	+/−
Organic	+/−
No data	n.a.

2.5.2. Topography

Regarding the topography, the slopes of each regional-zonal site unit were already classified by the FVA BW [48] in a GIS-layer into (a) lowlands and easy slopes (<30%); (b) medium slopes (30–45%); (c) steep slopes (>45%) and (d) others (e.g., gorges) [48,67]. The mapper overruled this classification in cases where specific site aspects may cause difficulties for logging operations on easy to medium slopes [48]. For example, both low infiltration and low bearing capacity are an indication for sites which could be overruled by the mapper.

Soil sensitivity was combined with slope classes. These two properties determine the risk of soil compaction and displacement, which are the main soil disturbances caused by vehicle traffic on forest floors [68,69]. This occurs mainly during extraction operations [70]. In addition to contributing to technical difficulties, terrain steepness also causes slippage [38] as well as erosion through runoff and soil loss [67,71] meaning that the highest soil deterioration level was experienced on slopes with inclinations above 20% [72].

Therefore, three in-stand transportation modes were identified with regard to both soil sensitivity and terrain (Figure 3): (1) Skid trails (ground-based forest operations on skid trails); (2) Tractor roads (ground-based forest operations on tractor roads) and (3) Road-based operations or cable yarding (no off-road traffic).

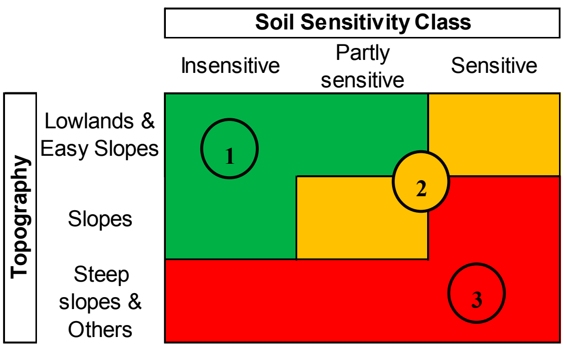

Figure 3. In-stand transportation modes with regard to soil sensitivity class and topography, focusing on timber extraction mode; where (1) indicates that traffic is possible (ground-based forest operations on skid trails); (2) indicates that low traffic is possible (ground-based forest operations on tractor roads); and (3) indicates that traffic is not possible (road-based operation/cable yarding).

2.5.3. Wood Dimensions

The DBH is a limiting factor for mechanized timber harvesting operations, depending on the type of harvester head [46]. Although harvester heads designed for diameters as large as 102 cm exist, 60% of the harvester heads on the European market have a smaller maximum felling diameter [73]. This large range in maximum felling diameters made it impossible to define a DBH limit for mechanized fellings. Kühmaier and Stampfer (2010) [46] reported a 50 cm DBH limit for mechanized fellings in softwood stands. Nevertheless, no harvester head specifically built for temperate European broadleaved tree species is on the market at this stage, and development focus is on diameters up to 35 cm [74]. Therefore, we assumed that felling would be carried out motor-manually whenever the DBH exceeded 50 cm for coniferous, and 35 cm for broadleaved tree species (Table 3).

When it comes to extraction, the choice of machine is restricted not only by terrain but also by the technical extraction mode and the volume or DBH of the trees (Table 4). For example, horses and small forestry crawlers can skid down slopes up to 45–50% [75–77], and drag volumes up to 0.6 m^3 and 1.2 m^3, respectively [78,79].

Table 3. Applied harvesting systems with regard to terrain slope and DBH.

Felling Mode	Slope	Tree Species	DBH (cm)
Chainsaw	Any	Any	any DBH
Wheeled harvester	Easy	Conifers	<50
Wheeled harvester	Easy	Broadleaves	<35
Tracked/tracked wheel harvester	Medium	Conifers	<50
Tracked/tracked wheel harvester	Medium	Broadleaves	<35

Table 4. Applied extraction systems with regard to terrain slope, log length and diameter at breast height (DBH).

Hauling Mode	Slope	Harvesting System	DBH or Volume
Skidder	Easy to medium	Tree-length/whole tree	Any
Forwarder	Easy to medium	Cut-to-length	Any
Small forestry crawler	Easy to medium	Tree-length/cut-to-length	<1.2 m^3
Horse	Easy to medium	Tree-length/cut-to-length	<0.6 m^3
Cable yarder	Any	Tree-length/whole tree	Any
Ground carriage	Easy to medium	Tree-length/cut-to-length	Any

To avoid stand damage and damage to natural regeneration, tree-length and cut-to-length operations were preferred.

2.5.4. Others Constraints

In BW, clearcuts exceeding an area of 1 ha need approval from the state forest authority [80]. Consequently, they play a minor role and were not considered in this study. Considering this, selective cuttings were assumed to be standard logging operations for final cuttings.

The cutting cycles of FDT 1, FDT 2, FDT 4 and FDT 6 were assumed to occur twice every 10 years with harvesting volumes corresponding to the volume increment [24]. FDT 3 (Reduced risk spruce forests) was assumed to be under selective logging—also known as Femelschlag—treatment, with thinning operations carried out every five years between 25 and 55 years of age, and final felling at 60, 65 and 70 years of age [60]. According to Forest Stewardship Council (FSC) standards for the region [81], the maximum cleared area during timber harvesting was set to 0.3 ha for all species, except oak and pine forests. For oak-mixed forests (FDT 5), the cleared area can be extended to 1 ha [81] (small-scale clear-cut) while still ensuring natural regeneration since oak is a species with intermediate shade tolerance.

3. Results

3.1. Forest Development Types

Conducting the GIS analysis made it possible to predict the location of the FDTs in 2050 in light of the expected climate change (Figure 4), namely a temperature increase of around 2 °C and a precipitation decrease of around 25 mm.

Coniferous-beech-mixed forests (FDT 1)

Under the above defined selection of the FDT layers, the main future forest type in BW state forests is expected to be coniferous-beech-mixed forest (FDT1) (Figure 4), with an area of 109,885 ha (29.0% of the study area). Results pertaining to the main coniferous tree species for this FDT indicated that 83,702 ha would be more favorable to silver fir (22%) than to spruce (7%).

Beech-coniferous-mixed forests (FDT 2)

At 77,736 ha (20.5%), beech coniferous-mixed forest types (Figure 4) are likely to be appropriate silvicultural options for responding to climate change.

Reduced risk spruce (FDT 3) and silver fir forests (FDT 4)

The results showed that risk-lessened spruce (Figure 4) and silver fir forests (Figure 4) will cover 21,053 ha (5.6%) and 8112 ha (2.1%) respectively. In contrast to reduced risk spruce FDT, silver fir forests (FDT4) are likely to occur mostly on sites where beech and spruce are not suitable but where silver fir is biologically important.

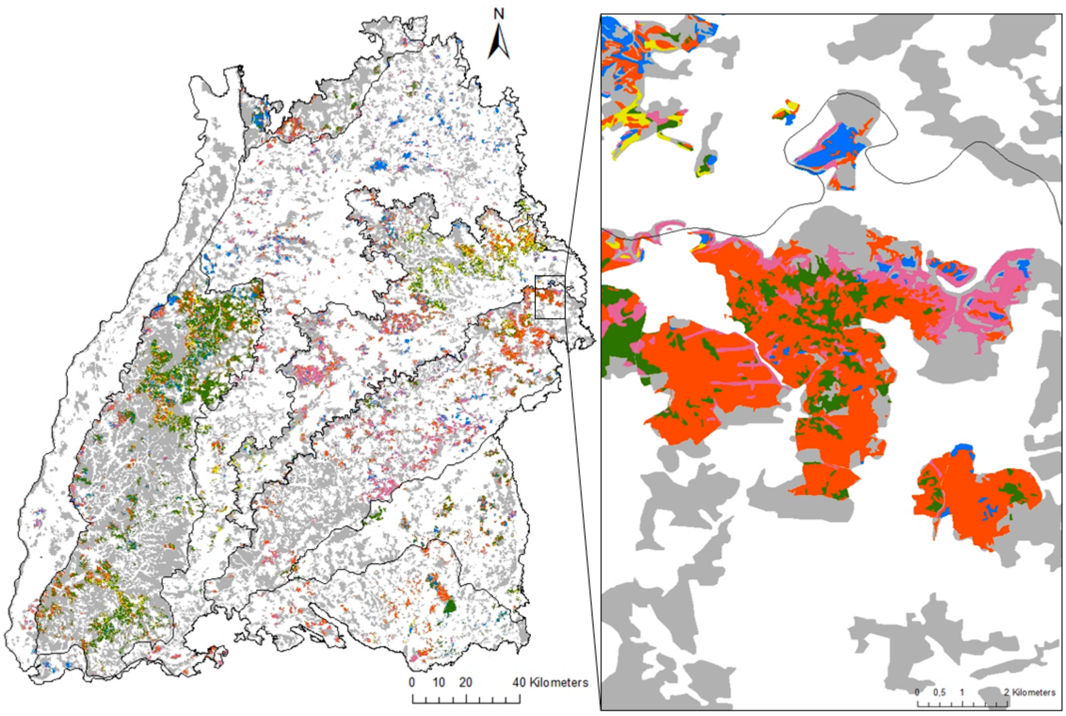

Figure 4. Location of the Forest Development Types (FDTs) in 2050 in BW state forests. In green: Coniferous-beech-mixed forests (FDT 1); in red: Beech-coniferous-mixed forests (FDT 2); in yellow: Reduced risk spruce forests (FDT3); in brown: Silver fir forests (FDT 4); in blue: Oak-mixed forests (FDT5); in pink: Beech-broadleaved forests (FDT6); in grey: Whole BW forest.

Oak-mixed forests (FDT 5)

The oak-mixed forest type includes common oak and sessile oak forest types (Figure 4) with high proportions of oak. The total area covered by this FDT will amount to 38,782 ha (10.2%).

Beech-broadleaved-mixed forests (FDT 6)

The beech-broadleaved-mixed forests (Figure 4) contain a similar proportion of beech (40–80%) to that of beech-coniferous-mixed forests. This FDT will represent an area of 58,571 ha (15.4% of the study area).

Remaining forest area

The aforementioned FDTs (1–6) are expected to cover 82.8% of the state forest of BW. The remaining 17.2% of the state forest of BW will be covered by other forest types. The main coniferous tree species may be European larch (*Larix decidua*), scots pine and Douglas fir or maple, ash, basswood and cherry as examples of broadleaved species.

3.2. Slope and Soil Sensitivity

The forest area analyzed with respect to slope classes as described in Section 2.5 is shown in Figure 5. The majority of the forest areas (55%) were located on lowlands and easy slopes. The proportion of soils sensitive to traffic was 33.5% with a majority of these located on lowlands and easy slopes (25.5%) with limited off-road traffic (Figure 5). Areas with greater terrain slope had lower proportions of soils sensitive to machine traffic.

This was supported by a GIS analysis showing that lowland sites suitable for broadleaved tree species were often more sensitive to traffic than hilly sites suitable for conifers, as shown in Table 5 for FDT 3, FDT 5, and FDT 6 (Reduced risk spruce, Oak-mixed and Beech-broadleaved-mixed FDTs, respectively).

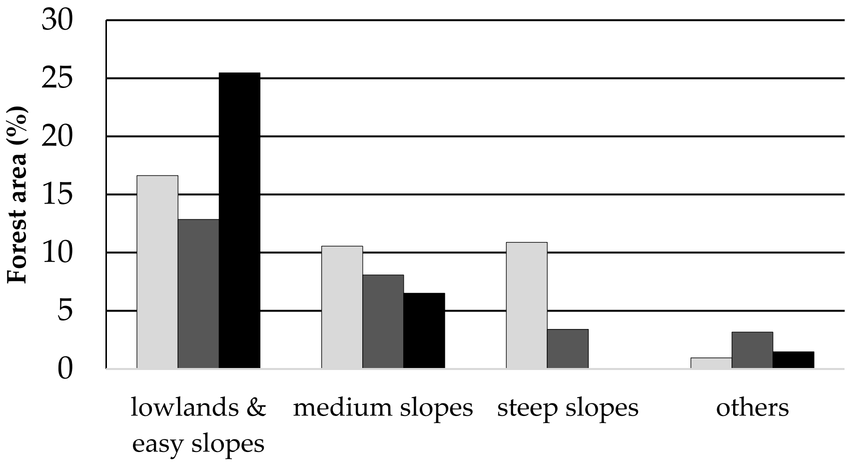

Figure 5. Distribution of the analyzed forest area with regard to topography and soil sensitivity to traffic (light grey: insensitive, dark grey: partly sensitive and black: sensitive), as a percentage of total forest area.

Table 5. Distribution of slope and soil sensitivity classes for three Forest Development Types: Risk reduced spruce forests (FDT 3), oak-mixed forests (FDT 5), and beech-broadleaved-mixed forests (FDT 6), in ha and %. The percentages are related to the area of each FDT respectively.

Slope Class	Soil Sensitivity	FDT 3 (Spruce), in ha	FDT 5 (Oak), in ha	FDT 6 (Beech), in ha
Lowlands and Easy slopes	Insensitive	6965 (33%)	3898 (10%)	2302 (4%)
	Partly Sensitive	2124 (10%)	2478 (6%)	11,670 (20%)
	Sensitive	1654 (8%)	18,012 (46%)	15,246 (26.0%)
Medium Slopes	Insensitive	3404 (16%)	5012 (13%)	2643 (4%)
	Partly Sensitive	1336 (6%)	2543 (7%)	5845 (10%)
	Sensitive	927 (4%)	2193 (6%)	5225 (9%)
Steep slopes and Others	Insensitive	2813 (14%)	3208 (8%)	9343 (16%)
	Partly Sensitive	1516 (7%)	1079 (3%)	2992 (5%)
	Sensitive Sum (ha)	314 (2%) 21,053	359 (1%) 38,782	3305 (6%) 58,571

3.3. Harvesting and Extraction Operations

Timber harvesting operations depend on varying factors such as forest type including species, tree dimension and quality, terrain slope and soil sensitivity. For the six selected FDTs, main harvesting and extraction methods (L) were determined (Figure 6 and Table 6), resulting in six different harvesting systems. Three different systems were applicable in each FDT. Overall results showed that a cable yarding system (L1) would be used on 29.1% (314,139 ha) of the total forest area. In the steep terrains, this figure would be 22.8%, and in terrain with medium slope, 6.3% (Table 6). It is very likely that the higher proportion of broadleaved trees in future forests will lead to an increased use of forestry tractors, because of both mandatory manual felling with optional cable support, and the limited trafficability of these sites. Operations will be conducted from tractor roads (23.0%) on sensitive soils and on medium slopes, whereas on insensitive soils, tractors will be operated on skid trails (18.4%) (Table 6). The combination harvester-forwarder could still be used in forests (i) with high proportions of conifer trees; (ii) with skid trail distances of 40 m when supported by chainsaw-felling (15.0%), or (iii) with skid trail distances of 20 m (4.0%) as a fully mechanized system (Table 6). On more sensitive soils, a combination of harvester and ground carriage or cable yarder is recommended (10.5%) (Table 6).

Table 6. Proportion of different felling and hauling systems (in %) applied in six selected Forest Development Types (FTDs) in Baden-Württemberg (BW). TR: tractor road, ST: skid trail.

Timber Harvesting and Extraction System	Used Abbreviation	Forest Area (%)
Chainsaw & Cable Yarder	L1	29.1
Chainsaw & Forestry tractor + Forwarder (TR)	L2	23.0
Chainsaw & Forestry tractor + Forwarder (ST)	L3	18.4
Chainsaw + Harvester & Forwarder (ST)	L4	15.0
Chainsaw + Harvester & Ground carriage/cable yarder	L5	10.5
Harvester & Forwarder (ST)	L6	4.0

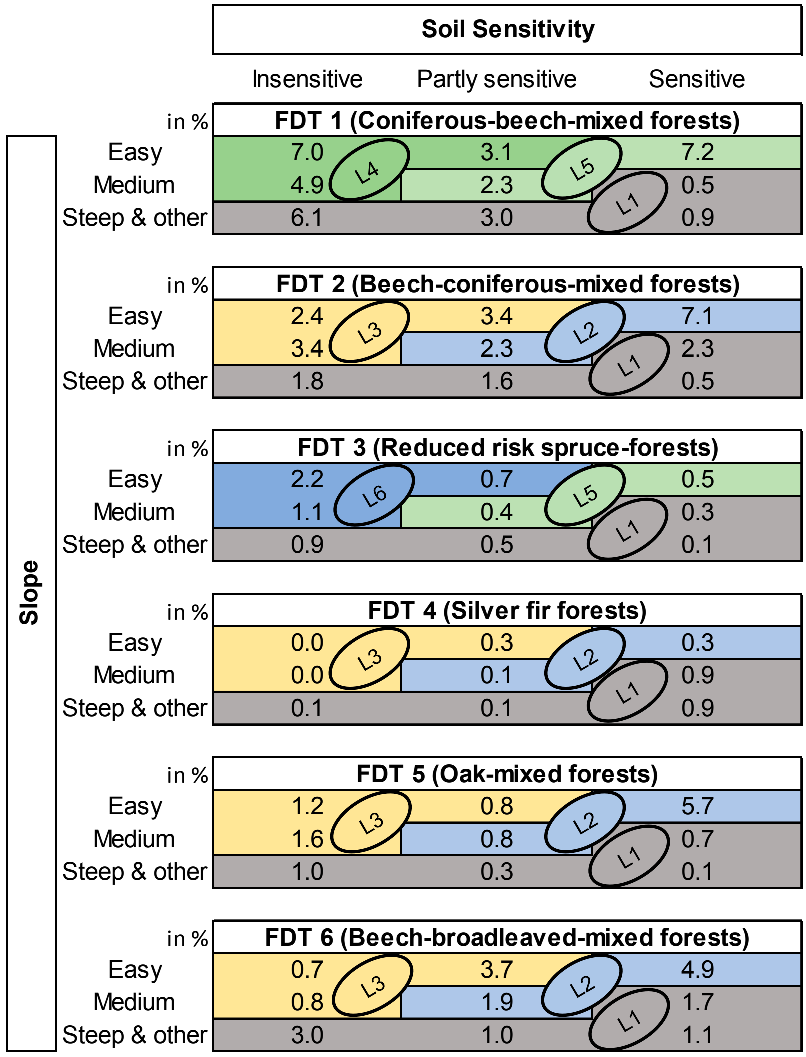

Figure 6. Proportion (in %, relative to the total area) of the application area of different logging operations (L) regarding the Forest Development Types (FDTs), where any insensitive soil class indicates that traffic is possible (ground-based forest operations on skid trails); a partly sensitive soil class indicates that low traffic is possible (ground-based forest operations on tractor roads); and a sensitive class indicates that traffic is not possible (roadways/cable yarder forest operations) (c.f. Figure 3). L1 to L6 as described in Table 6.

4. Discussion

4.1. Advantages of Applied Methods

The use of GIS to identify Forest Development Types that will be relevant in the future turned out to be a powerful planning tool. GIS has great potential, given that data are increasingly available in digital format, and that data queries can be conducted quickly and large areas can be easily included in analyses. To the best of our knowledge, no study has addressed the future location of FDTs. Most of the assessments found in literature do not consider the actual location of future forests when estimating biomass potentials, interpreting qualitative changes in forests, or developing suitable harvesting operation strategies. By including the location, it was possible for the first time to derive harvesting systems that consider local constraints, such as soil trafficability and topography, for these forest types. We managed to quantify the expected changes in forest operations, to show trends in timber harvesting operations and to make recommendations for stakeholders.

4.2. Tree Species Composition

Climate envelope models conducted for BW show the lability of spruce forests to future climatic conditions in the lowlands [7,17]. This is one of the reasons why the proportion of spruce trees has been continuously reduced over the last 30 years as a management objective: the proportion declined from 43.5% in 1987 to 34.0% in 2012 for all forest land in BW [56]. One main policy objective of Baden-Württemberg is to achieve equal proportions of coniferous and broadleaved tree species at least in state forests [4]. Therefore, this study considers that in future forests spruce, silver fir, oaks, and beech will together represent more than 80% of the state forests of BW. Our results showed that coniferous species (spruce and silver fir) would be the dominant species in 37% of future forests whereas broadleaved species (beech and oak) would be dominant in 46%. This is clearly in line with results from Reif [4], who estimated that spruce and silver fir would grow on 39%, beech on 31% and oak on 8% of the future forest land base. Other authors have used climate envelope models to predict the future range and shifts of single tree species (mostly spruce and beech) in Europe, in Germany and in BW [6,7,17,82]. Our results showed that there would be a continuation of the trend of decreasing shares of conifers, as the proportion of forest types dominated by spruce or silver fir in state forest in BW is predicted to decline from 47.7% [83] to 37% by 2050. This situation will likely be a major issue for the wood processing industry, which mostly depends on softwood [84]. Softwood timber is of particular importance to the European construction sector [85]. The use of timber for structural products shows the greatest potential for global climate change mitigation compared to any other use of wood [86], which is mainly due to the substitution of carbon-intensive materials [30] and the long-term carbon storage of construction wood products [84].

Our results showed that the area covered by broadleaved trees will likely increase in the future. Several studies have shown the benefits of admixture of broadleaved species in conifer stands as they play a key role in forest stability and adaptation of forests to pathogens, storms and climate change. It is generally agreed that mixed stands are more resistant to biotic and abiotic disturbances [30,87] because "with an increasing number of functionally different species, the probability increases that some of these species can resist external disturbances or changing environmental conditions" [88]. Native European deciduous trees tend to be less affected by climate change than conifers [6]. In particular, the susceptibility of Norway spruce to natural hazards is much greater than that of beech, the most common tree species in BW. Moreover, a significant reduction of the financial risk can be achieved by mixing large blocks of broadleaved species with conifer stands [87]. In line with the current management strategy, beech and oaks are increasingly admixed in spruce and pine forests [30].

Non-native tree species are likely to become more important economically. Douglas fir, red oak (*Quercus rubra* L.) and Japanese larch (*Larix kaempferi* Carr.) have good adaption potential as climate conditions in their native growing regions are similar to those predicted for parts of Germany (Hickler et al., 2012). Douglas fir is often seen as a promising silvicultural option. This is supported by the German Federation of Forest Research Institutes (DVFFA) [89], whereas the German Federal Agency for Nature Protection (BfN) classified Douglas fir as an invasive species resulting in recommendations for limiting its growing area [90].

4.3. Adaption of Species Composition

The study focuses on a temperature increase of around 2 °C by 2050. Simulations and climate projections for the end of the 21st century showed that global warming will probably lie between 1.7 and 4.4 °C [91]. The higher the temperature increase, the more uncertain the predictions of tree species, FDTs and adapted forest operations are. If the temperature increase exceeds 2 °C, the adaption of existing forests will become limited [16,92]. Research on phenotypical plasticity at the single tree level, as well as on evolutionary adaption at a population level is needed.

The objective of changing forest structure and composition in order to increase the resistance and resilience of forests, is a challenge considering the long rotations under current management practices. The development towards more mixed woodland is a long-term process, and many stands first need to grow to an age where the forest can be converted [25]. The transition from current forests to the FDTs should be a fluent transition with adaptive management. The aim is to enable the FDTs to respond to change. The response option facilitates the transition to new conditions [12]. This study focused on the timber harvesting and extraction systems from future FDTs, and the transition state were not considered. The adaptive transition management has to be defined on a local scale, depending on current species composition and future FDTs. For some specific cases, Forst BW published silvicultural guidelines [24].

For private forests, the related costs and efforts could hinder the owners to apply adaptive management. Moreover, as the current income from conifer forests is much higher than those from broadleaved forests, private owners may be reluctant to adopt new management practices. Since 36% of BW forest land belongs to private owners [56], it is essential to support private owners for the success of climate change adaptation policies. The shift in the species composition within the time frame 2050–2100 will not be achieved on all forest areas, but it should be seen as a goal to initiate adaptive management no later than 2050.

4.4. Topography

Our findings showed that 55% of the forest area is located within the lowlands and easy slopes class. Previously, the third national forest inventory from 2012 (BWI^3) found that 73% of the whole forest area in BW has a terrain slope below 30% [29]. This difference may result from the mapping methodology. The guideline [48] defines that lowlands and easy slopes have a maximum inclination of 30%; however, the mapper can overrule the classification and move the topographic class “lowlands and easy slope” into the class “medium slope”. Differences also occurred regarding steep slopes. According to the BWI^3, 18% of BW forest land area has a slope above 41%. In comparison, the data of our study assessed that approximately 24% of the area was on steep slope. It is obvious that the mapper over-evaluated the slopes in order to include site specificities that hamper harvesting operations. This is considered advantageous, since the resulting trafficability becomes more realistic.

4.5. Soil Sensitivity

The use of heavy machinery in forest management has significantly increased. It enhances productivity, reduces occupational health and safety risks, and lessens stand damage, but may seriously damage forest soils [64,93]. Soil compaction is a major cause of human-induced forest soil degradation [68] and “has been considered a principal form of damage associated with logging, restricting root growth and reducing productivity” [94]. Soil protection is becoming increasingly important [95], and even more soil protection will be needed in order to ensure a sustainable long-term wood supply with aggravating weather conditions [34] such as shorter frozen ground periods and higher precipitation are expected in winter, and this will have an impact on low risk traffic possibilities [96]. Conducting timber harvesting and extraction operations in late summer/early fall could offer low risk traffic opportunities [96].

Small-scaled mapping of soil types and sensitivity assists in the choice of adapted harvesting and extraction methods. Our results concerning soil sensitivity showed that around 30% of forest soils in BW could be considered sensitive to traffic, which is in line with further literature: Berleth et al. [97] even figured a proportion of 41%.

Soil water balance was indirectly included in the analysis as an input parameter for the species suitability map. However, water balance might be a useful additional layer to more precisely determine soil sensitivity as ”the severity of compaction caused by forest machinery is greatly influenced by soil water content” [98].

4.6. Changes in Timber Harvesting and Extraction Systems

There is quite a variety of timber harvesting and extractions systems applied in BW. Nevertheless, the BWI^3 quantified the forest area according to forest operation conditions. According to the BWI^3, on 73.6% of the state forest area, any timber harvesting and extraction system can be used [29]. Furthermore, on 8.7% of the forest state area, only machines dedicated for steep terrain can operate and on 15.1%, no off-road traffic is possible [29]. These values do not consider tree species or tree DBH. To assess actual timber harvesting and extraction systems we had to make the following assumptions on terrain where off-road traffic was possible: (i) broadleaved trees are felled motor-manually and extracted by skidders and (ii) conifers are felled by harvesters and extracted by forwarders. Considering these tree species-based assumption, we were able to give a rough overview of current forest operations. Motor-manual systems with ground-based timber extraction would be used on 45%, harvester-forwarder systems on 40%, and motor-manual systems with cable yarder extraction on 15% of the state forest area.

Following these assumptions, the area harvested using harvesters will decrease from 40 to 30% and extraction based on forwarders even more from 40 to 19% in future. Compared to our results, the importance by area of cable yarding systems will nearly double from 15 to 29%, whereas the area with motor-manual felling and skidder extraction will remain quite constant.

4.7. Machinery

The changes in tree species composition and the growing awareness of forest soil protection may induce major technical changes for harvesting and extraction machines. The increasing number of heavy machinery, especially harvesters and forwarders, could easily lead to an over-capacity [99]. On the other hand, new technologies such as the lowland-cable-yarder, six- and eight-wheeled forestry tractors, tire width and inflation pressure, as well as cable-assist systems, help to reduce negative impacts on soil [38,100,101]. Nevertheless, such technologies (especially the lowland-cable-yarder and cable-assist systems) still need to demonstrate economic feasibility. Cable-assist systems are becoming increasingly common, but only a few studies have been published, and "the actual implementation and understanding of its limitations, is in its infancy" [102]. Therefore, and because "no European country has yet implemented specific cable-assist rules" [102], we were not able to incorporate cable-assist systems for steep slopes and sensitive soils in our study. The use of cable-assist systems could replace cable yarding operations on some sites. Therefore our estimate of cable yarding proportions could be overestimated.

The higher proportions of broadleaved trees may also change the usage of machinery on site. For safety reasons, it is useful to use a winch to support the felling process by pulling down the trees. This allows a controlled felling of the tree in the planned felling direction. Winches, small forestry crawlers, or forestry tractors equipped with winches can be used, and might become more popular for logging operations. Therefore, we recommend the use of special forestry tractors with winches. Finally, the use of harvesters for the felling and processing of both conifers and broadleaved trees may improve felling productivity, as well as work safety [103].

For future harvesting and extraction methods, it may be possible that autonomous or semi-autonomous systems will become popular. Autonomous forwarders are believed to have considerable commercial potential as they are more profitable [104,105]. However, some technical challenges are still associated with automating machines [106]. Potential is therefore seen for autonomous direct-loading systems, where a conventional harvester places processed trees directly into the bank of an autonomous forwarder [106] which could be a ground carriage system such as, for example, the ground carriage Pully developed by Konrad (Konrad Forsttechnik GmbH, Preitenegg, Austria) [107].

5. Conclusions and Outlook

In order to discuss the impact of climate change on forest structures and future harvesting operations and to map the location of the FDTs, a regional case study was performed using GIS. It was possible to prescribe distinct operations for different areas and types of forests in the state forests of the BW region. The analysis showed that, within the time horizon 2050–2100, coniferous-beech-mixed forests will probably be the main forest type in the state forest of BW, covering 29% of the total forest area. Moreover, continuous tree cover (the German "Dauerwald" concept [62]) will be applied to at least 67% of the forest area, which will certainly lead to changes in forest operations. Using trafficability classes, which are dependent on terrain slope and forest soil sensitivity to traffic, it was possible to provide recommendations regarding harvesting and extraction systems for each FDT. Data availability of current forest composition coupled with current forest management practices would be a nice asset for comparing our results to present forest operations.

Among the analyzed FDTs, 50% of the area with slopes lower than 30% has soils that are extremely sensitive to traffic. Additionally, 23% will be in terrain with slopes higher than 45% where traffic faces technical limitations. Thus, there is a strong requirement for technical developments in forest operations, especially in extraction methods such as the lowland-cable-yarders, improved forestry tractors, and forwarders to reduce ground pressure and slippage, and cable-assist systems as well as light autonomous systems. Increasing the ratio of broadleaved forests with continuous tree cover will probably increase the number of motor-manual felling operations, which in turn leads to an increased demand for manpower in the forestry sector. Also given the fact that new machines require highly specialized machine operators, it might become a challenge to acquire enough qualified forestry workers.

Future harvesting and extraction operations in more structured forests will become multifaceted through a combination of machines and manpower. These complex work systems increase the risk of accident for forestry workers when compared with fully mechanized systems which are actually linked with the lowest number of reported accidents. Enhanced and intensified work safety training and instruction guides should be developed for future timber harvesting and extraction systems.

For future research, tree-level growth models should be developed in order to improve resolution and degree of detail. This study could be used as a basis for the application of different scenarios. Through the simulation of different management strategies for each FDT and trafficability class, the prospective harvest assortments could be described with greater accuracy. Thus, in forest operations with varying harvesting intensities, assortments and machinery need to be evaluated with regard to GHG emissions.

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