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Global analysis of the slope of forest land

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Forests of the world constitute one-third of the total land area and are critical for e.g. carbon balance, biodiversity, water supply and as source for bio-based products. Although the terrain within forest land has a great impact on accessibility, there is a lack of knowledge about the distribution of its variation in slope. The aim was to address that knowledge gap and create a globally consistent dataset of the distribution and area of forest land within different slope classes. A Geographic Information System (GIS) analysis was performed using the open-source QGIS, GDAL and R software. The core of the analysis was a digital elevation model and a forest cover mask, both with a final resolution of 90 m. The total forest area according to the forest mask was 4.15 billion hectares whereof 82 per cent was on slope $< 15°$. The remaining 18 per cent was distributed over the following slope classes, with 6 per cent on a 15–20° slope, 8 per cent on a 20–30° slope and 4 per cent on a slope $> 30°$. Out of the major forestry countries, China had the largest proportion of forest steeper than 15° followed by Chile and India. A sensitivity analysis with 20 m resolution resulted in increased steep areas by 1 per cent point in flat Sweden and by 11 per cent points in steep Austria. In addition to country-specific and aggregated results of slope distribution and forest area, a global raster dataset is also made freely available to cover user-specific areas that are not necessarily demarcated by country borders. Apart from predicting the regional possibilities for different harvesting equipment, which was the original idea behind this study, the results can be used to relate geographical forest variables to slope. The results could also be used in strategic forest fire fighting and large-scale planning of forest conservation and management.

Introduction

Of the earth's land area, 31 per cent is covered by forests (FAO, 2010; Keenan *et al*., 2015). Forests play a key role in regulating the earth's climate through the carbon cycle; more carbon is sequestered and stored per hectare (ha) in forests than other types of land cover (Eliasch, 2012). Forest cover has increased by ~7 per cent since the 1980s (Song *et al*., 2018). Nevertheless, every year, ~3.7 billion m^3 of roundwood is harvested around the world, and of those forests, according to Curtis *et al*. (2018), 70 per cent are later reforested while 30 per cent remain deforested (see also Global Forest Watch, 2020). Out of the total global harvest, 1.9 billion m^3 are classified as industrial roundwood (FAO, 2016). There are 31 countries that harvest at least 10 million m^3 of industrial roundwood per year, and together they harvest ~1.7 billion m^3 or 90 per cent of the total annual harvest in the world (FAO, 2016). Five countries harvest more than half of the total harvested volume in the world: the USA, Russia, China, Canada and Brazil (FAO, 2016). Industrial roundwood is harvested and extracted in numerous ways around the world. There are many reasons for the choice of harvesting systems, equipment and methods in different countries (see Gibson *et al*., 1986; Nordfjell *et al*., 2004; Ghaffariyan, 2014). Typically, the physical properties of the land to be harvested play a major part in determining the most suitable equipment and methods. See for example the systematic, Geographic Information System (GIS) based approach in Kühmaier and Stampfer (2010).

Certain key physical properties are commonly recorded in most countries before harvesting begins (Sessions, 2007; Uusitalo, 2010). In the Nordic countries and Canada those physical properties are organized in a structured and harmonized manner into a 'terrain classification system' (Anon., 1969; Samset, 1975; Mellgren, 1980). Physical properties have historically been used to determine which areas are suitable for harvesting machinery at all, and for accessible areas, a given classification describes the level of difficulty that machinery would experience when negotiating the terrain. Since machinery came to be widely used in forest harvesting, the capabilities of all machines have increased and thus affected such classifications in terms of what is difficult and what is possible (Malmberg, 1980; Nordfjell *et al*., 2010). In the Swedish terrain classification system there are three properties: (1) ground conditions, (2) surface structure and (3) slope (Berg, 1992). The *ground conditions* property describes the load-bearing capacity of the ground and is determined largely by the soil type, moisture content and vegetation type (Malmberg, 1989). Favourable ground conditions have good load-bearing capacity and indicate the possibility of harvesting at many different times of the year and in most kinds of weather conditions without negative impacts on the soil, whereas more problematic ground conditions restrict the characteristics of the machines that can be used (available driving force, ground pressure, ground clearance and traceability, etc.) as well as the season and weather conditions when harvesting is possible (Malmberg, 1989; Han *et al*., 2009). The second property, *surface structure,* describes the level of difficulty with respect to number and size of rocks and other obstacles within a harvest area (Malmberg, 1989). Surface structure does not usually affect the season when harvesting can be undertaken but indicates which machinery to use and its productivity on the specific site. Like ground conditions, surface structure can place specific demands on the machine characteristics ground clearance and traceability.

The third property, slope, is defined as the average terrain slope within a particular harvest area. Slope is measured in degrees, or as a percentage calculated as the change in elevation divided by the relevant horizontal distance. Slopes approached in different directions affect the harvesting equipment in different ways; for example, an uphill slope requires sufficient driving power and traction, a downhill slope requires good braking and a side slope can cause a vehicle to overturn if the machine is not sufficiently stable. A stable machine is ideally low and wide; however, there is a trade-off with turning radius and ground clearance. The maximum slope that can be negotiated with certain machinery can vary due to surface structure, vehicle–terrain interaction and operator skill level (Visser and Stampfer, 2015). Usually, tracked machines can handle steeper slopes than wheeled machines as long as the surface structure is not too rough (Nordfjell *et al*., 2004). If the terrain becomes too steep even for tracked machines, the last option is cable- or air-based systems (Greulich, 1999; Nordfjell *et al*., 2004). According to the International Labour Organization's code of practice for forestry work, rubber-wheeled harvesters and forwarders should not operate on terrain steeper than 35 per cent (∼19°), tracked harvesting equipment should not be used on land exceeding 40 per cent (∼22°), and no ground-based equipment at all, even that designed specifically for steep terrain, should work beyond 50 per cent (∼27°) (ILO, 1998).

Apart from the definite limits in slope for different kinds of equipment, there are also cases when work is still possible, but it has to be carried out with extra care. For example, a forwarder extracting timber can handle much steeper slopes upwards and downwards than sideways, and therefore strip roads may have to be oriented parallel to the slope. Furthermore, the maximum side slope is less when the forwarder is loaded than unloaded. Specific limits for side slope with and without loads were specified for forwarders in the 1960s and 70s in Sweden, as outlined in 'Driving in Steep Terrain**'** (Malmberg, 1980). The specific limits state that driving across a side slope steeper than 15° should be avoided, and if unavoidable, extra detailed planning of the work is required (Malmberg, 1980). For a fully loaded forwarder and/or rough terrain, the limit for a side slope is even less. In addition, guidance has been provided for soil preparation/scarification in the Swedish context: the maximum slope for downhill work is given as ∼22°, and ∼17° for uphill work (Rülcker, 1991).

A global dataset containing slope classes for the forest land of different countries would be useful in strategic wood harvest planning and many other applications. Modern remote sensing data and methods facilitate a wide range of analyses, not only in research related to climatology and geology, but also in the field of forest operations (Talbot *et al*., 2017). An overall picture of forest operations in mountainous areas is presented by Heinimann (2004). Therein, 28 per cent of the world's forests are classified as mountainous, although the slope that counts as mountainous is not defined (Heinimann, 2004). Another application of large-scale slope data is in predicting and fighting wild fires affecting forest land: foreseeing difficulties with accessibility due to steep forest terrain could potentially increase efficiency when deploying fire-fighting resources. Analysis of remote sensing data is, in general, a desirable approach when the results ought to be consistent and comparable between different geographical regions and countries. Manually collected information, for example country reports of forest area, forest volume, etc. to FAO, have a tendency to be more or less inconsistent in quality and resolution (Matthews and Grainger, 2003). Due to the expected demands of comparability in future statistical analyses and modelling studies, the GIS approach comes out as a relevant choice of method.

The aim of this study was to create a globally consistent raster dataset of slope classes on forest land and make this freely available online. A secondary aim was to present data on global and national forest land distribution in relation to a number of slope classes, ranging from relatively flat to very steep, as well as forest area per slope class, on a national level.

Methods

The overall concept of this analysis was to combine data on terrain slope with data on forest/non-forest land cover, to assess slope data within forested areas. The terrain slope-data were separated into four classes. The slope of the forest areas was extracted by country.

A GIS analysis was performed. To manipulate and modify the data, several open-source tools and software were used (Table 1): QGIS (Development Team, 2019), GDAL (GDAL/OGR contributors, 2019) and R (Core Team, 2018). The core of the analysis was based on elevation data from the German TanDEM-X mission (Rizzoli *et al*., 2017) as well as forest cover data from NASA satellites (Hansen *et al*., 2013). A vector dataset including country borders was also used for the division of data into countries (Esri®, 2019).

To calculate slope, the digital elevation model (DEM) developed from the TanDEM-X mission (Rizzoli *et al*., 2017) was used. The original elevation model has a resolution of 12 m, but it has subsequently been aggregated to 90 m resolution and made available freely for scientific use by Deutsche Zentrum für Luft- und Raumfahrt (DLR). For this study, the freely available 90-m resolution data were used.

Table 1 Software and tools used in the analysis and a short explanation of their application

Tool	Application	Reference
GDAL		
gdaldem slope	Slope calculation from elevation data	(GDAL/OGR contributors, 2019)
gdalinfo	Various applications when information from one raster was transferred to another, for example resolution	(GDAL/OGR contributors, 2019)
gdalwarp	For aggregation of forest cover data to resolution of slope data	(GDAL/OGR contributors, 2019)
gdal.calc.py	Combining the slope data with the forest cover data using raster multiplication	(GDAL/OGR contributors, 2019)
QGIS		
zonal histogram within QGIS	Applied to count the number of pixels with certain values within countries	(QGIS Development Team, 2019)
R:		
rgdal reclassify	Reclassification of slope data into classes	(Bivand *et al*., 2019)
R function area	To compute the area of each pixel in a raster, considering the data are unprojected	(Hijmans, 2019)
R function exactextractr	Used to extract sum of area-pixels within countries, similar to zonal statistics	(Baston, 2019)

To convert the elevation data to slope data, a corresponding slope raster was computed from the DEM using a method of eight grid points with unequal weights (Horn, 1981). This is the standard method applied for slope calculations in GDAL. Scale factors were applied to compensate for the fact that the horizontal positions of pixels in the DEM were presented in degrees while the elevation was in metres. To avoid projecting the global DEM on a flat surface, as one would do with smaller study areas, *different* scale factors were used for every change in latitude. The following formula was used for the scale factors:

$$\text{Scale factor} = 111\,320 * \cos\frac{\text{latitude} * \pi}{180}, \tag{1}$$

where 111 320 is a constant representing the number of metres in one degree longitude at the equator. The scale factor changed gradually according to equation 1 while moving towards the poles because one degree equals fewer and fewer metres in the east–west direction when moving away from the equator.

All slope pixels were placed in one of four slope classes. The classes were defined by slope intervals: $\leq 15°$, >15 to $20°$, >20 to $30°$ and $>30°$. The four slope classes are of unequal width. The first one (0–15°) is wider, while the next (15–20°) is narrower. This division was based on how harvesting equipment generally negotiates different levels of slope: basically, most machines can handle a slope ~15°, while a slope of 17° can start to get challenging for some systems, especially on side slopes and with a load. This explains the choice of the first class (0–15°). A slope of 20–22° is commonly considered to be the limit for rubber-wheeled harvesters and forwarders, which is the rationale for designating the next class (15–20°). However, this limit can be pushed substantially with the help of cable-assist systems (Visser and Stampfer, 2015). Tracked machines, for example harvesters with self-levelling carriages, can usually handle slopes ~30° before they start to loose grip (Cavalli and Amishev, 2019) and beyond that special features have to be added, for example wheels mounted on individually movable arms and cable assist. On this basis, the classes of 20°–30° and $>30°$ were selected.

To calculate the share of forest land in each slope class, the Hansen forest cover data for the year 2000 (Hansen *et al*., 2013) were used. The Hansen forest cover data are a raster dataset with pixel values between 0 and 100 corresponding to a crown cover percentage within each specific pixel. To create a binary forest/non-forest (FNF) mask, a threshold of 25 per cent crown cover was applied for each pixel in the Hansen forest cover data. With that threshold, the calculation of forest area per country shows good overall alignment to FAO (2010) forest cover data. A lower threshold of 10 per cent was tested because it corresponds to FAO's definition of forest land. The lower threshold however, when applied on the Hansen forest cover data, resulted in significant overestimations of forest land in certain large countries such as Canada. The FNF mask was aggregated from the original 30×30 m resolution to 90×90 m to correspond to the slope data.

The intersection of 'slope' and 'forest' rasters was computed in the GDAL raster calculator. The number of pixels in a certain slope class was divided by the total number of forest land pixels in each country by also applying the Esri® (2019) vector data for country borders. The operation was repeated for each slope class in all countries. For this, the QGIS tool *Zonal histogram* was used.

Finally, the forest area was calculated for the FNF mask, pixel by pixel using the area function of the R raster package (Hijmans, 2019). With this function, the area was defined vertically from above and the function handles unprojected raster data in such a way that the areas could be calculated with approximations only within each pixel instead of over two digit numbers of latitudes. Due to the data structure of the DEM, a more standard tool would only use four different scale factors for the area calculation,

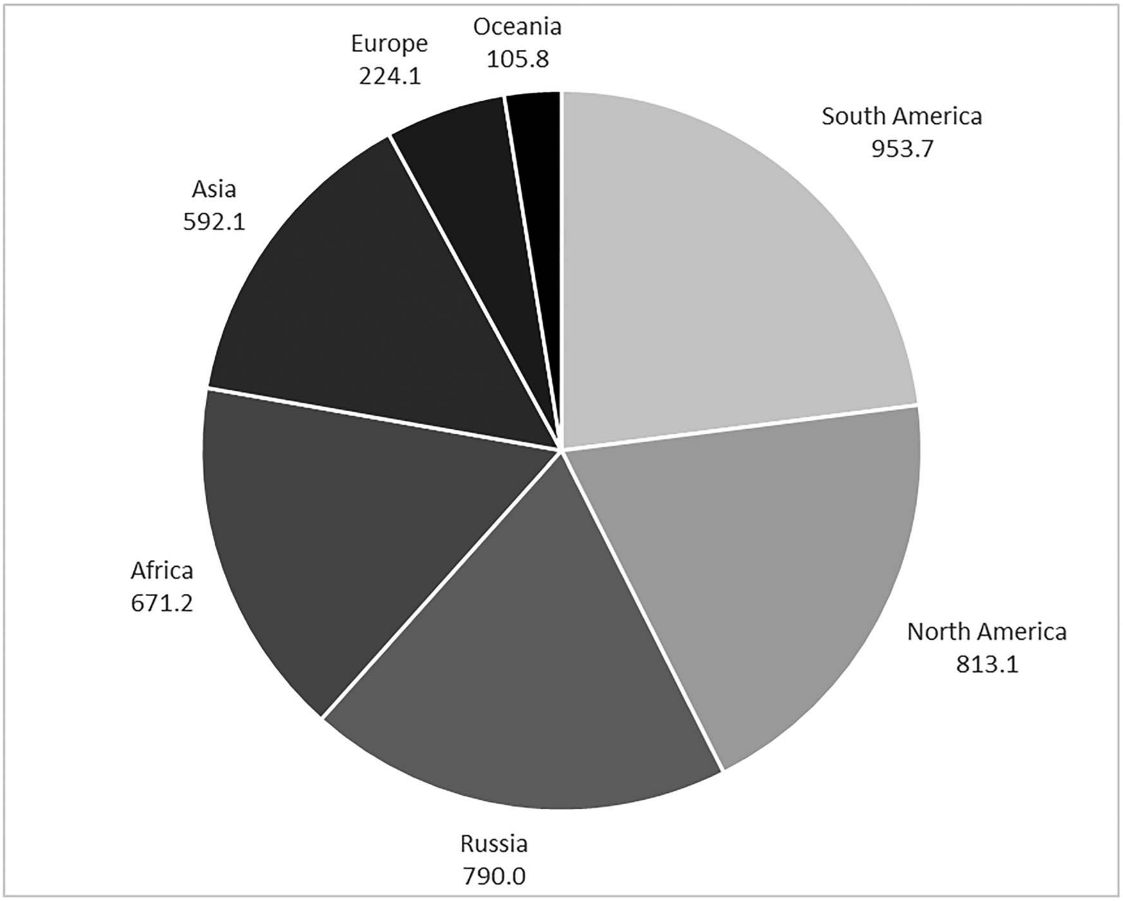

Figure 1 Forest area (Million ha) per continent calculated from the forest mask. Russia is displayed separately due to its size and presence in both Europe and Asia.

while the area function uses one for each latitude. The result is a value of area for each pixel, which was then summarized per country polygon using the *exact extract* function (Baston, 2019). All aggregated results per continent were computed, with Russia in a separate category due to its size and because it spans two continents, thus, Russia's forest areas are not part of Europe's or Asia's in the results.

Results

The total forest area according to the applied forest mask is 4.15 billion ha, corresponding to 32 per cent of the total land area of the earth. The forest area on the six continents varied between 106 million ha in Oceania and 954 million ha in South America. Russia alone has 790 million ha (Figure 1).

There is great variation in slope distribution between countries (Table 2). Of all the world's forests, 82 per cent were found on slopes between 0 and 15 degrees. The remaining 18 per cent was distributed in a declining pattern over the steeper slopes. The second slope class 15–20° supported a smaller percentage of the forest land than the third due to its narrower interval, 5° compared with 10° (Figure 2). Large areas of steep forests are typically found in the mountains, whereas flat terrain forests are found in, for example, Russia, Africa and the Amazon rainforest (Figures 3 and 4). In the 'High Coast' region of Sweden (Figure 3d), some very steep areas can be found close to rivers. In the same way, it is also possible to find flat forest areas in an overall steep landscape, for example south eastern China (Figure 4c). The distribution of slope in forest land varies greatly between continents, with Asia and Africa being the two extremes. Africa has a large share of forest land on flat terrain and almost no forest on very steep terrain (>30°). In contrast, Asia has <60 per cent of its forest land on flat terrain and ~10 per cent on very steep terrain (Figures 3–5).

The 10 countries that harvest the most roundwood each year account for ~70 per cent of the total global harvest (FAO, 2016). Finland, Sweden and Brazil all have at least 95 per cent of their forest land within the lowest slope category (0–15°). The forest land in the US, Russia and Canada shows common patterns of distribution over the four slope classes, having between 80 and 90 per cent of their forest area on slopes ~15° (Figure 6). There are three countries that stand out with a low (~50 per cent) share of forest land on slopes between 0 and 15°: Chile, China and India (Figure 6). Even more extreme are Latvia, Belarus and Uruguay with 99–100 per cent of their forest land in the lowest slope category (Table 2).

Table 2 The forest area and share of forest land within each of four slope classes (%) for every country

Country	Forest area (1000 ha)	0–15° slope (%)	15–20° slope (%)	20–30° slope (%)	>30° slope (%)
Afghanistan	264	8.3	6.1	27.0	58.6
Albania	715	24.3	18.7	34.1	22.8
Algeria	1333	44.9	21.8	26.6	6.7
Andorra	20	5.6	7.5	31.6	55.3
Angola	63 277	97.3	1.6	1.0	0.1
Anguilla	2	99.6	0.4	0.1	0.0
Antigua and Barbuda	19	88.2	5.7	5.7	0.4
Argentina	40 128	90.8	2.9	3.8	2.5
Armenia	346	20.5	17.5	39.3	22.7
Aruba	0.04	100.0	0.0	0.0	0.0
Australia	46 011	79.3	8.7	9.5	2.6
Austria	4380	35.6	12.1	24.5	27.8
Azerbaijan	1324	39.9	14.0	26.2	19.9
Bahamas	263	99.9	0.0	0.0	0.1
Bangladesh	2049	89.1	5.7	4.4	0.8
Barbados	5	94.6	5.0	0.4	0.0
Belarus	9278	100.0	0.0	0.0	0.0
Belgium	891	92.3	4.7	2.7	0.4
Belize	1731	89.3	5.5	4.4	0.8
Benin	609	99.6	0.2	0.2	0.0
Bermuda	0.1	99.5	0.0	0.0	0.5
Bhutan	2622	9.6	10.9	35.5	44.0
Bolivia	65 091	88.2	3.5	5.3	3.0
Bosnia and Herzegovina	2750	51.1	17.1	22.1	9.7
Botswana	55	96.0	2.3	1.7	0.1
Brazil	526 085	95.3	2.6	1.8	0.3
British Virgin Islands	5	26.1	23.8	46.6	3.5
Brunei	528	89.9	4.8	4.7	0.6
Bulgaria	4193	56.3	16.7	20.6	6.4
Burkina Faso	1	99.8	0.1	0.2	0.0
Burundi	848	72.5	13.8	12.2	1.5
Cambodia	9216	92.8	3.8	3.0	0.4
Cameroon	34 196	93.9	2.9	2.7	0.5
Canada	427 259	88.7	3.7	4.1	3.5
Eastern Canada	187 688	95.5	2.6	1.5	0.4
Western Canada	238 814	81.2	4.9	6.9	7.0
Cape Verde	7	26.6	23.4	34.2	15.8
Cayman Islands	9	99.9	0.0	0.0	0.1
Central African Republic	51 683	99.8	0.1	0.1	0.0
Chad	954	99.0	0.5	0.5	0.0
Chile	18 080	47.3	11.9	19.6	21.3
China	170 712	42.4	17.1	25.7	14.8
Colombia	82 315	81.4	5.8	8.7	4.1
Comoros	133	68.0	14.5	12.0	5.5
Congo	28 817	98.1	1.3	0.5	0.0
Costa Rica	3920	70.4	11.8	13.5	4.3
Croatia	2444	75.5	11.3	10.3	2.9
Cuba	4008	86.5	5.7	6.4	1.4
Cyprus	131	37.5	21.6	33.1	7.8

Continued

Table 2 Continued

Country	Forest area (1000 ha)	0–15° slope (%)	15–20° slope (%)	20–30° slope (%)	>30° slope (%)
Czech Republic	3108	81.1	10.6	7.3	1.0
Denmark	654	99.2	0.6	0.2	0.0
Djibouti	0.0001	100.0	0.0	0.0	0.0
Dominica	68	46.5	19.0	24.2	10.3
Dominican Republic	2626	71.4	11.8	13.1	3.8
Ecuador	19 115	72.0	8.8	13.0	6.1
Egypt	353	100.0	0.0	0.0	0.0
El Salvador	1029	71.7	13.8	12.2	2.2
Equatorial Guinea	2639	89.8	5.0	4.5	0.7
Eritrea	0.01	27.3	18.2	45.5	9.1
Estonia	2634	99.9	0.1	0.0	0.0
Ethiopia	15 494	79.5	9.3	9.1	2.2
Falkland Islands (Islas Malvinas)	2	59.1	18.3	20.8	1.7
Fiji	1502	72.6	15.0	10.6	1.7
Finland	21 625	98.2	1.2	0.5	0.1
France	17 200	74.0	8.5	11.0	6.5
French Guiana	8187	96.9	2.3	0.7	0.0
Gabon	24 607	94.1	3.9	1.9	0.1
Gambia, The	21	100.0	0.0	0.0	0.0
Gaza Strip	0.04	100.0	0.0	0.0	0.0
Georgia	3204	29.1	12.4	26.9	31.6
Germany	12 695	81.2	8.4	7.7	2.7
Ghana	7915	96.7	2.0	1.1	0.1
Gibraltar	0.1	38.0	14.7	30.7	16.6
Glorioso Islands	0.02	100.0	0.0	0.0	0.0
Greece	3994	40.9	19.5	27.7	11.8
Grenada	26	72.3	14.5	11.0	2.1
Guadeloupe	90	75.6	10.6	10.4	3.5
Guatemala	7820	72.1	10.0	12.8	5.1
Guernsey	1	91.3	3.2	2.1	3.4
Guinea	11 316	93.1	4.1	2.3	0.5
Guinea-Bissau	1409	99.9	0.0	0.0	0.0
Guyana	19 059	95.6	2.3	1.7	0.4
Haiti	887	60.0	15.4	18.3	6.3
Honduras	7849	60.3	17.9	18.3	3.5
Hungary	2053	89.9	6.0	3.6	0.4
India	41 758	55.4	11.5	18.9	14.2
Indonesia	160 216	78.5	8.6	9.9	3.0
Iran	1806	28.8	16.2	31.1	23.9
Iraq	21	70.0	3.7	12.2	14.1
Ireland	867	90.3	5.0	3.5	1.2
Isle of Man	14	74.0	11.7	10.3	4.0
Israel	33	68.2	15.0	14.3	2.5
Italy	9650	37.3	16.2	25.2	21.3
Ivory Coast	17 978	98.6	0.8	0.5	0.1
Jamaica	764	73.4	11.9	11.2	3.6
Japan	26 046	45.2	17.6	25.2	12.0
Jersey	2	84.7	6.5	6.9	2.0
Jordan	3	49.9	28.9	20.8	0.5
Kazakhstan	4455	51.9	11.2	20.3	16.6
Kenya	3950	85.3	6.9	6.1	1.6

Continued

Table 2 Continued

Country	Forest area (1000 ha)	0–15° slope (%)	15–20° slope (%)	20–30° slope (%)	>30° slope (%)
Kyrgyzstan	745	14.5	9.7	28.6	47.2
Laos	19 326	52.5	18.1	23.8	5.5
Latvia	3564	99.8	0.2	0.0	0.0
Lebanon	73	33.4	20.4	29.5	16.7
Lesotho	12	46.0	16.2	26.6	11.2
Liberia	9432	97.4	1.7	0.8	0.1
Libya	11	69.1	13.7	12.7	4.5
Liechtenstein	10	25.5	6.8	20.0	47.7
Lithuania	2352	99.6	0.3	0.1	0.0
Luxembourg	103	74.6	12.8	11.0	1.6
Macau	0.01	77.8	22.2	0.0	0.0
Macedonia	843	30.6	21.4	35.4	12.6
Madagascar	18 549	80.1	10.7	7.8	1.4
Malawi	2235	78.5	11.0	9.2	1.3
Malaysia	29 266	74.4	12.8	11.4	1.4
Maldives	0.02	76.0	0.0	0.0	24.0
Mali	104	95.6	3.0	1.4	0.1
Malta	0.1	75.0	3.8	3.0	18.2
Martinique	70	71.5	13.0	10.5	5.0
Mauritania	0.04	100.0	0.0	0.0	0.0
Mauritius	82	81.2	7.5	8.5	2.7
Mayotte	30	81.4	12.6	5.5	0.6
Mexico	55 339	63.2	12.3	17.3	7.2
Moldova	375	92.1	6.2	1.6	0.2
Monaco	0.2	19.5	21.5	46.3	12.7
Mongolia	4487	49.5	25.2	21.7	3.6
Montenegro	658	41.8	17.4	25.4	15.3
Montserrat	4	46.9	19.7	25.4	8.0
Morocco	756	45.3	18.5	26.7	9.4
Mozambique	37 030	96.4	1.8	1.6	0.2
Myanmar (Burma)	43 413	55.8	15.5	21.2	7.5
Namibia	14	91.8	2.6	4.6	0.9
Nepal	5315	25.9	10.9	30.4	32.8
Netherlands	624	99.6	0.2	0.1	0.2
Netherlands Antilles	7	94.7	3.7	1.4	0.2
New Caledonia	1423	55.0	16.3	22.3	6.5
New Zealand	10 960	41.3	14.0	23.1	21.6
Nicaragua	7878	88.4	6.6	4.5	0.5
Niger	0.01	100.0	0.0	0.0	0.0
Nigeria	12 883	93.0	2.9	3.5	0.6
North Korea	5384	23.5	20.0	41.2	15.3
Norway	11 358	58.4	12.0	14.8	14.8
Oman	0	0.0	33.3	0.0	66.7
Pacific Islands (Palau)	28	97.8	1.4	0.2	0.6
Pakistan	1152	10.2	9.0	29.2	51.6
Panama	5580	73.4	12.3	11.6	2.6
Papua New Guinea	42 413	70.5	10.0	13.8	5.7
Paraguay	24 954	99.7	0.2	0.1	0.0
Peru	78 043	82.1	4.9	7.7	5.2
Philippines	18 332	65.2	13.6	15.9	5.3
Poland	10 590	92.1	4.0	3.4	0.6

Continued

Table 2 Continued

Country	Forest area (1000 ha)	0–15° slope (%)	15–20° slope (%)	20–30° slope (%)	>30° slope (%)
Portugal	2478	74.1	13.0	11.1	1.8
Puerto Rico	520	73.1	14.1	11.5	1.4
Reunion	177	67.8	11.5	7.9	12.9
Romania	8057	52.8	16.8	21.5	8.8
Russia	789 986	84.8	5.7	6.2	3.3
Rwanda	697	65.9	16.4	15.8	2.0
San Marino	1	49.6	29.9	14.0	6.5
Sao Tome and Principe	14	50.0	14.2	19.9	16.0
Saudi Arabia	0.01	100.0	0.0	0.0	0.0
Senegal	170	99.9	0.0	0.0	0.0
Serbia	3178	51.9	19.0	22.9	6.2
Seychelles	1	99.5	0.0	0.0	0.5
Sierra Leone	6045	94.4	3.5	1.9	0.2
Singapore	14	98.4	0.3	0.0	1.2
Slovakia	2399	49.3	18.9	23.6	8.3
Slovenia	1330	48.9	15.2	20.8	15.1
Solomon Islands	2411	64.1	14.4	16.1	5.5
Somalia	140	96.7	1.3	1.3	0.7
South Africa	7082	70.9	12.6	12.5	4.0
South Korea	5357	33.1	23.1	35.0	8.7
Spain	11 888	54.7	16.3	20.8	8.2
Sri Lanka	4038	86.2	6.2	6.1	1.5
St. Kitts and Nevis	8	49.7	18.7	23.9	7.8
St. Lucia	50	66.4	18.4	12.1	3.1
St. Pierre and Miquelon	4	91.0	5.0	3.5	0.6
St. Vincent and the Grenadines	26	50.2	20.0	20.8	8.9
Sudan	17 181	98.4	0.6	0.8	0.2
Suriname	13 853	95.6	2.7	1.6	0.1
Swaziland	584	78.1	12.2	8.8	0.9
Sweden	27 826	94.6	3.1	1.8	0.5
Switzerland	1575	30.2	11.0	22.4	36.4
Syria	117	47.3	19.7	24.5	8.4
Taiwan	2331	23.3	12.2	30.4	34.0
Tajikistan	78	13.9	7.8	31.2	47.1
United Republic of Tanzania	34 029	91.8	4.3	3.4	0.5
Thailand	20 422	66.4	15.5	15.7	2.3
Togo	800	90.7	4.8	3.9	0.6
Trinidad and Tobago	377	87.0	6.0	6.0	0.9
Tunisia	243	73.3	15.9	9.5	1.3
Turkey	10 879	42.0	18.6	26.5	12.9
Turkmenistan	13	74.9	4.5	10.2	10.4
Turks and Caicos Islands	7	100.0	0.0	0.0	0.0
Uganda	10 000	94.4	2.4	2.6	0.7
Ukraine	11 587	85.5	5.3	6.6	2.6
UK	3809	80.9	8.0	7.5	3.6
US	284 896	80.4	7.1	8.4	4.1
Uruguay	1739	98.8	0.9	0.3	0.0

Continued

Table 2 Continued

Country	Forest area (1000 ha)	0–15° slope (%)	15–20° slope (%)	20–30° slope (%)	>30° slope (%)
Uzbekistan	133	51.4	6.1	19.4	23.1
Vanuatu	1040	70.9	11.4	12.8	4.9
Venezuela	56 997	84.7	6.7	6.5	2.1
West Bank	1	69.9	15.9	12.9	1.2
Vietnam	16 847	49.7	17.2	24.7	8.3
Virgin Islands	10	81.2	11.9	6.6	0.3
Yemen	0.3	22.2	11.6	34.4	31.8
Zaire	211 196	97.4	1.4	1.0	0.1
Zambia	31 691	98.0	1.1	0.9	0.1
Zimbabwe	2415	79.3	9.9	9.3	1.5
Africa	671 203	95.1	2.5	2.0	0.4
South America	953 741	90.4	3.6	4.0	2.0
Russia	789 986	84.8	5.7	6.2	3.3
North America	813 066	82.7	6.1	7.2	4.0
Oceania	105 761	70.6	10.1	13.1	6.2
Europe	224 113	67.7	10.4	13.8	8.1
Asia	592 145	57.3	13.9	19.4	9.4
World	4 150 015	81.7	6.5	7.9	3.9

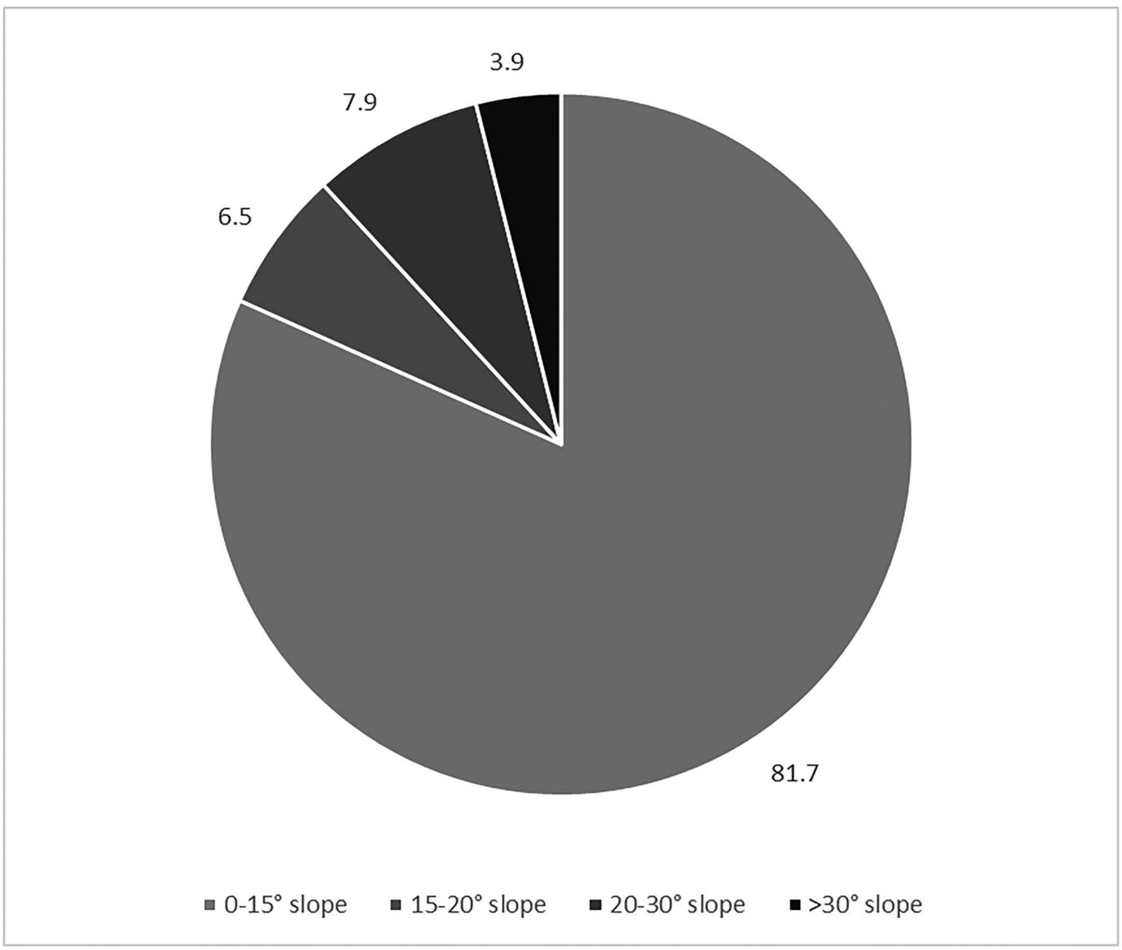

Figure 2 World's forest land distribution in the four slope classes (%).

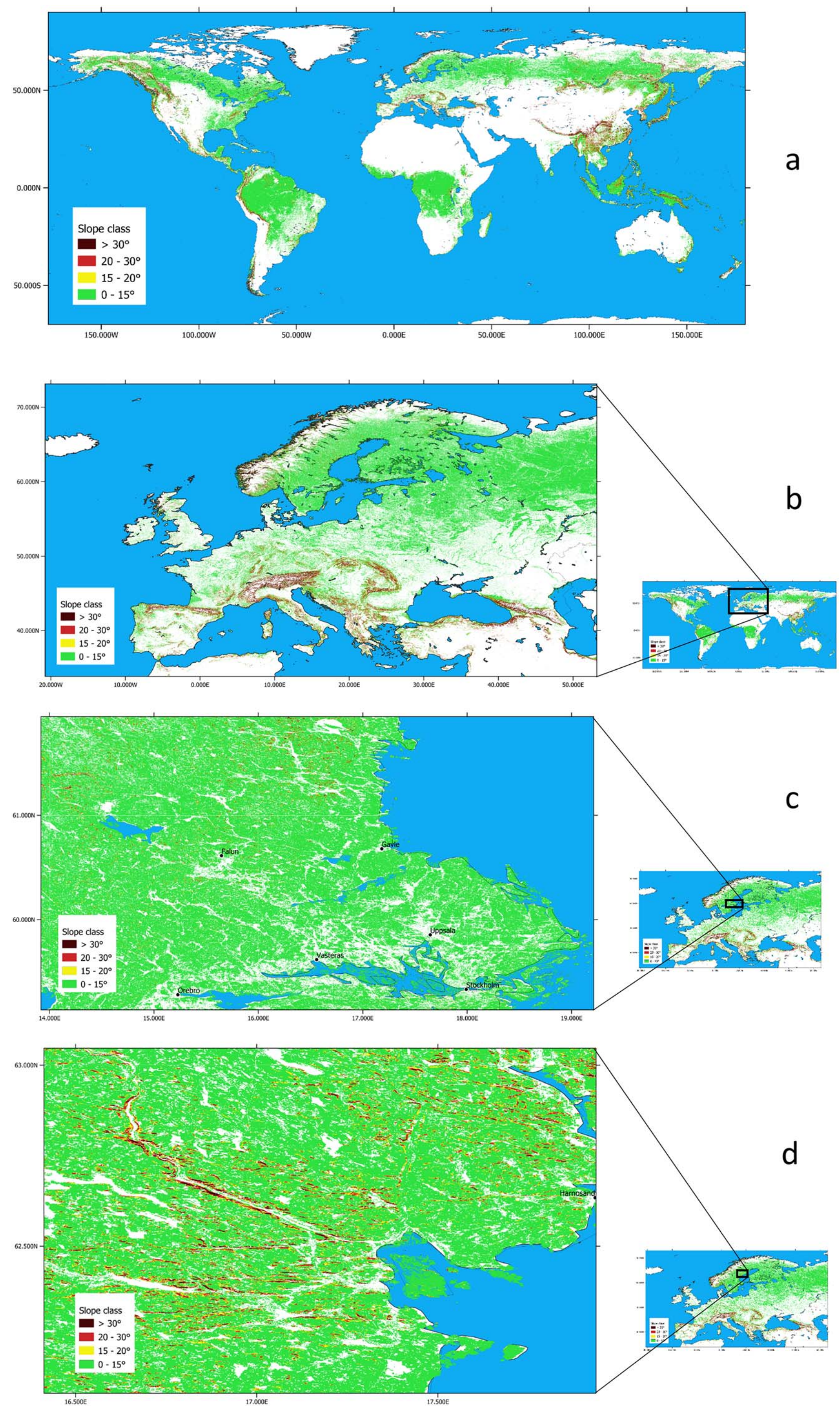

Figure 3 World map and detailed enlargements in which each forest land pixel is represented by a colour that reflects a slope class. The white areas are non-forest. From top to bottom, the following areas are shown: (a) World (except Antarctica), (b) Europe, (c) Sweden area around Stockholm and (d) Sweden 'High coast'**.**

Discussion

The main contribution of this study is to provide a global table of the share and area of forest land in four different slope classes, country by country (Table 2). The origin of this study was lack of knowledge, or at least consistent data, of slope in forest land, from a forest operations point of view. The results for Sweden in this study are similar to those presented by Von Segebaden (1975). However, the slope classes in Von Segebaden (1975) follow the Swedish Terrain Classification (Anon., 1969), whereas

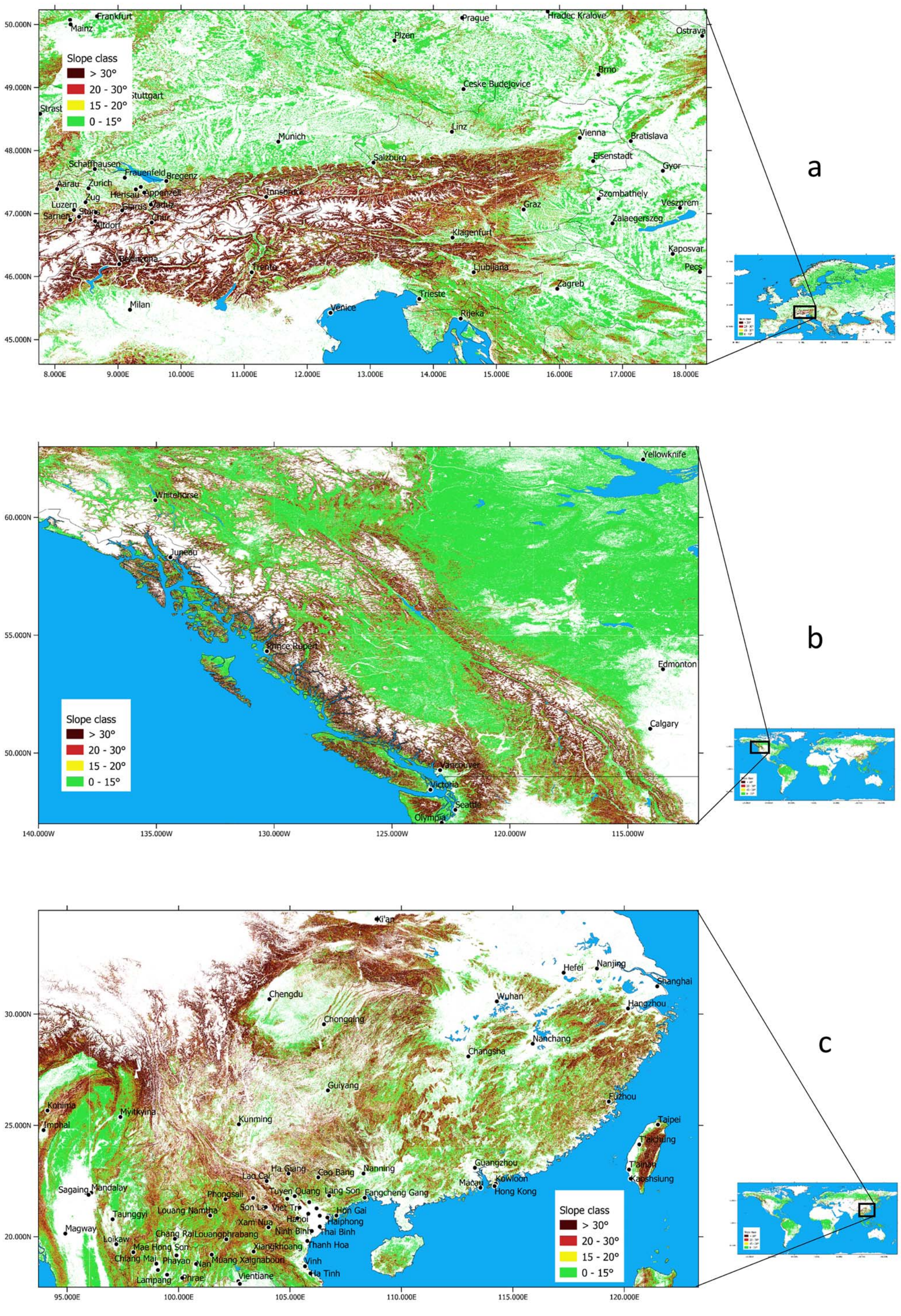

Figure 4 Detailed enlargements in which each forest land pixel is represented by a colour that reflects a slope class. The white areas are non-forest. From top to bottom, the following areas are shown: (a) Austria, (b) British Columbia, Canada and (c) south-eastern China.

in this study the classes were selected with reference to modern machinery and a worldwide application. Nevertheless, the two steepest slope classes are quite similar, 18–27° and >27° in Von Segebaden (1975) compared with 20–30° and >30° in this study. Combined, these two slope classes account for 2 per cent of the Swedish forest land in both Von Segebaden (1975) and this study. Furthermore, Von Segebaden (1975) reports that 92 per cent of the Swedish forest land has slopes of 0–11°, while this study shows 95 per cent of forest land on a slope between 0 and 15°, a quite good alignment. In Turkey, Demir (2010) states that 'Productive forests are generally found in mountainous areas which have 40–80 per cent gradient', i.e. with a slope > 22°. The

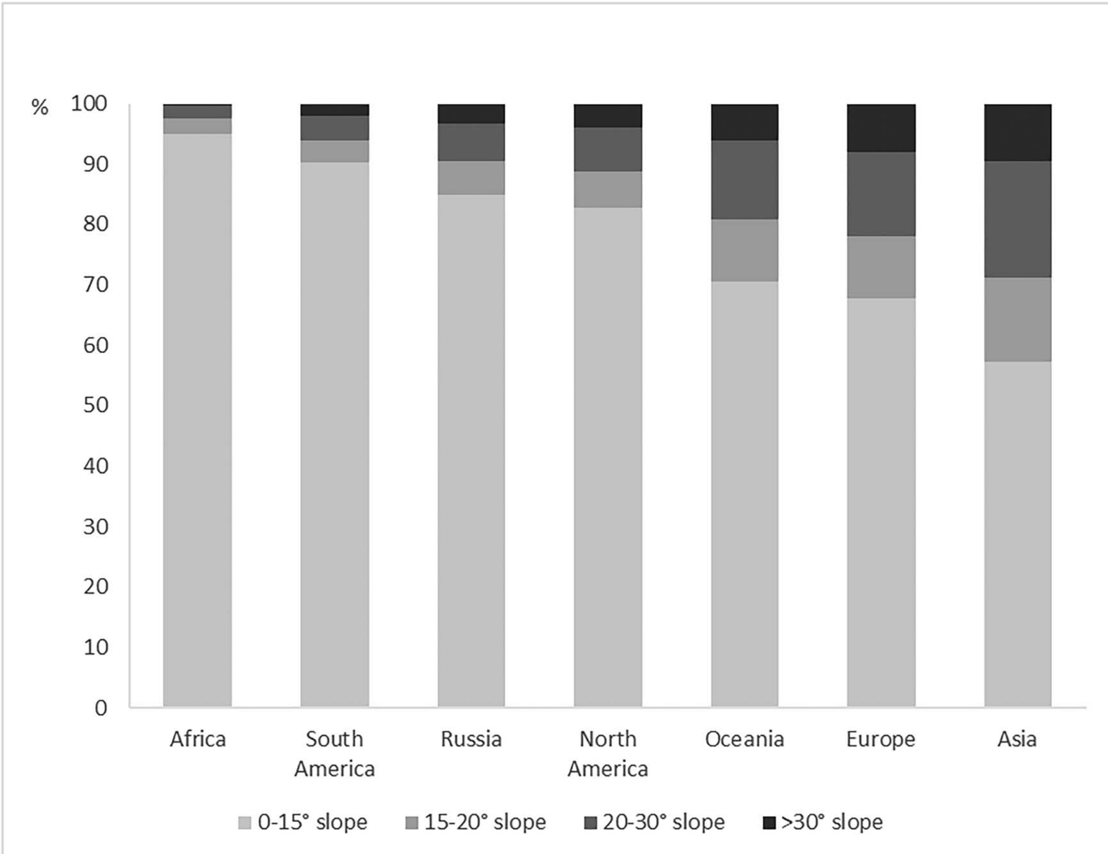

Figure 5 Forest land distribution over the four slope classes on the six continents with forestry. Russia is displayed separately and its distributions are not included in the figures for Asia or Europe.

share of forest land > 20° in Turkey according to this study is 40 per cent, one should remember though that productive forest land is only a subset of the forest targeted in this study, which means that the forests that are harvested could well be aligned with our results.

Global maps of forest cover as well as the forests timber volume, tree density and other forest characteristics have been produced for many years. The use of DEMs for various purposes is also widespread. The novelty of this study was to bring together these existing datasets to create new data. In the research field of forest operations, information pertaining to terrain slope has always been important, but, as already stated, the information has not existed in a consistent, structured and internationally comparable form before. Furthermore, the dataset attached to this study (Lundbäck *et al*., 2020) is detailed enough to facilitate analysis on smaller geographic areas than reported in Table 2, such as municipalities, see Figure 3 for a Swedish example of this.

Technical methodology implications

Forest cover data

To mask out all areas that are not forests in this study, technically any available geographic data relating to forest cover could have been used, although with different results. The distribution of forest land in the four slope classes could change with different so-called FNF masks. Potential differences depend on whether the distributions are the same in areas covered by the FNF mask and areas in reality, both regarding false positive and false negative forest pixels. For the area calculation (Table 2), on the other hand, a reasonably accurate FNF mask will directly come out as superior to a less accurate one since the official area of forest in countries is a key figure that can be found in many data sources. The benchmark for forest areas in this study was the widely known and applied Forest Resources Assessment published every 5 years by FAO, more specifically FAO (2010). Initially, an FNF mask that originated from the same TanDEM-X mission as the height data (Martone *et al*., 2018) was tested, however the misalignment with FAO data (FAO, 2010) was too large to be acceptable. The differences were almost exclusively underestimates and they seemed to be largest in boreal areas. For example, Sweden ended up with only half of its forest area compared with FAO figures, which in turn align well with figures widely accepted by foresters in the country. To provide reliable and valid data, the Hansen forest cover data were applied as the FNF mask instead of the TanDEM-X data.

The Hansen data

The definition of forest in this study is simply all trees that exceed a height of 5 m (Hansen *et al*., 2013) combined with 25 per

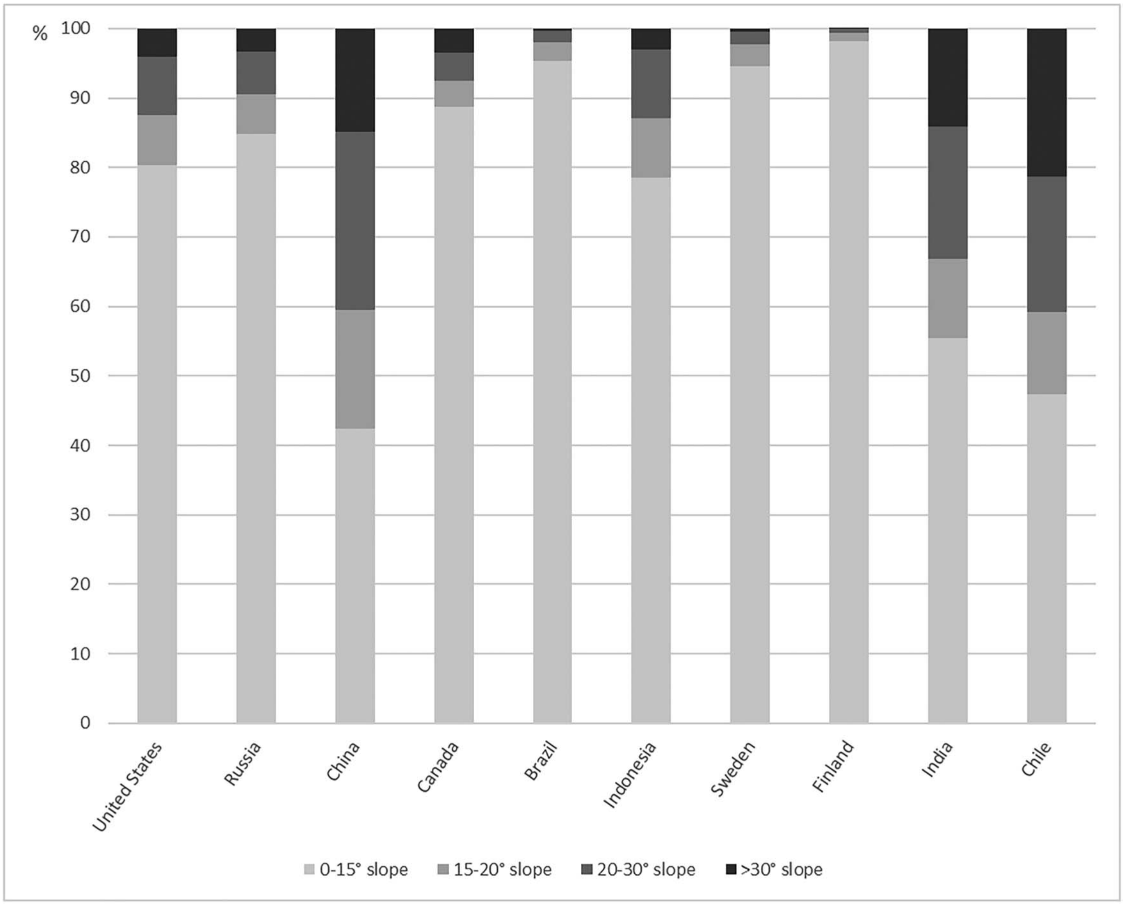

Figure 6 Forest land distribution in the four slope classes in the 10 countries that harvest 70 per cent of the world's industrial roundwood per year (US, Russia, China, Canada and Brazil together account for 50 per cent of the world's harvest). Annual harvest decreasing from left to right.

cent crown cover per 90 × 90 m pixel. The threshold of 25 per cent crown cover resulted in a total forest area of 4.15 billion ha worldwide, a figure that aligns well with FAO's corresponding figure of 4.03 billion ha (FAO, 2010). Although our results in general align quite well with FAO data, different definitions of forest can have a large impact on the results of forest area calculations in specific countries. For example, the estimated forest area in Australia deviated substantially between this study (∼46 million ha) and the FAO data (∼150 million ha). For the Australian country report to FAO, data from the governmental investigation *Australia's State of the Forests* were used, and this has a somewhat different definition of forests:

'An area, incorporating all living and non-living components, that is dominated by trees having usually a single stem and a mature or potentially mature stand height exceeding 2 m and with existing or potential crown cover of overstorey strata about equal to or greater than 20 per cent. This includes Australia's diverse native forests and plantations, regardless of age. It is also sufficiently broad to encompass areas of trees that are sometimes described as woodlands' (ABARES, 2018).

Differences in tree height are probably the main source of deviations. In a dry country of vast size like Australia there are large areas with trees or shrubs with a height between the thresholds of 2 and 5 m. Those trees will cause problems with the comparison, as discussed by Miller (2016). However, another important difference in definition is that this study takes a *tree cover* approach, while the definition from the Australian government report focuses on *land use*. This implies that, for example, fresh clear-cuts will not appear as forest in our data even though they will be reforested in a couple of years, and thus should not be seen as permanently deforested. Differences in definition are unavoidable in large-scale comparisons, the differences may not even be a problem depending on whether the comparisons are made between datasets or among countries within the same dataset. The implications of definitions are, however, always important to bear in mind.

Finally, it should be noted that the data for the FNF mask were gathered around the year 2000 and that the data behind the figures in FAO (2010) are probably some years more recent, depending on what data each country used for reporting to the FAO. However, we believe that this only result in minor discrepancies in forest area between the two kinds of data, compared with the issues discussed above.

Effects of aggregation of the FNF mask

When the FNF mask was aggregated from its original 30 × 30 m resolution to 90 × 90 m, some information was lost. The lower resolution was preferred for the FNF mask to match the slope data, as described earlier. To evaluate the extent to which the aggregation resulted in lost information, the forest area in each country was calculated for both resolutions. The absolute difference between those areas was calculated for each country, and for Sweden (a flat country) the difference was 0.003 per cent of the total forest area. The corresponding number for Austria (a steep country) was 0.006 per cent, and for Australia (a country where the FNF mask deviated from FAO data) 0.004 per cent. Globally, the corresponding total figure was 0.003 per cent. The global figure was calculated by adding all national absolute differences in forest area and dividing that sum of differences by the total forest area in the world. These measures of error for the aggregation may be overestimated since the difference for each country was calculated from an area defined by at least 10 per cent crown cover in each pixel in the Hansen forest cover data. Eventually, for the main analysis a threshold of 25 per cent crown cover was used, which decreased the forest areas and thus possibly also the differences.

The height and slope data

The original DEM used for calculating slopes in this study was produced using the interferometric synthetic aperture radar (InSAR) technique. In this specific case, the TanDEM-X and TerraSAR-X satellites gathered X-band radar data for generation of the DEM. Since X-band is short wave (~3 cm), the signals will not penetrate dense crown covers in forested areas and thus result in a 'surface model' in forest areas and a 'ground model' in open areas. The bias introduced in the DEM due to this circumstance was not investigated further in this study because it was considered a minor factor for a large-scale analysis, as is the case here.

For the slope calculation, a DEM resolution of 90 × 90 m was chosen for this study as a compromise between computational load and level of detail, and also because the dataset was released freely for scientific use in that specific resolution. The basis for proceeding with that resolution was a case study on the effects on slope distributions in Sweden and Austria of using higher resolutions (20, 50 and 90 m). In the case study, country-specific forest cover masks of higher quality were applied, and national projections of the data were produced, ensuring that errors were as small as possible in parts of the analysis that did not concern the resolution. The case study revealed a pattern of increased areas of steep forests with increased resolution. For Swedish forests, which mainly grow on flat terrain, the proportion of forest land with a slope over 20° was 0.7 per cent units higher when the resolution was 20 × 20 m compared with 90 × 90 m. Since Sweden only had between 0.3 per cent (lowest resolution) and 1 per cent (highest resolution) of forest land on a slope over 20°, the change of 0.7 per cent point corresponds to a percentage of ~230 per cent.

For Austrian forests, which mainly grow on steep terrain, the proportion of forest land over 20° increased by almost 11 per cent points for the 20 m resolution compared with 90 m, but the percentage was only ~25 per cent. The proportion of forest land on a slope over 20° changed from 40 to 50 per cent.

Eleven per cent points is a difference worth noting, however, the transition from 20 × 20 m to 90 × 90 m resolution does not mask the main patterns of the forest land distribution in slope classes, either within countries or in comparisons between them. Steeper areas within a 90 × 90 m pixel that only appear in data with finer resolution may be small enough to be avoided by machines during harvest. Even though the slope distributions are slightly inaccurate with the bigger pixels, the result can be just as valuable as a description of accessibility from a forest operations point of view, however, more on strategic level than the detailed operational planning level. Under the presumption that the relationship between share of steep forest land in a country and the error factor is linear, with Sweden at the 'flat' end of the scale (0.7 per cent point) and Austria at the 'steep' end (11 per cent points), one could make rough calculations to correct for the error depending on resolution for a specific country. However, the correction factor needs to be critically examined and this was not tested in any way by the authors of this paper.

Further research and use

This paper comes not only with the results (Table 2), but also free to use, actual raster data containing the values of the four slope categories per pixel (Lundbäck *et al*., 2020). Thus, researchers and practitioners from all over the world can make use of it. Future research is likely to be directed towards separating the forested areas that are used as production forests from natural conservation forests. To date, there has been no global dataset of plantations that enables such a separation; however for a specific country, geographic data that distinguish these different kinds of forests often exist. As an opposite approach, global data on undisturbed forest areas have been presented by Potapov *et al*. (2008) and a combination of that kind of data with the slope data from this study could lead to new insights in the physical properties of the undisturbed versus disturbed forest areas. An interesting topic for future research would also be to compare different forest cover datasets from different years by looking at forest areas country by country.

Since the slopes are presented only for forested areas in the dataset, the impact of slope on forest inventory variables such as primary production can be assessed at a large scale. Virtually, anything connected to forests that can be quantified at the global scale can be related to slope with the help of this dataset. Analyses of the historical impact of humans on forests, e.g. land use change and control of forest fires in different countries and continents, would be of great use to better understand the present state of our planet. For example, Figure 3 reveals that Europe has a low proportion of its forests on flat terrain compared with South America and Africa. Part of the explanation could be the overall terrain of the different continents; however it could as well be a symptom of humankind's impact on nature. It is known that, historically, lots of forest land has been converted to agricultural land in Europe; it is also evident that this process is now ongoing in, for example, South America. The world has seen huge forest fires during recent years and the challenges in fighting and controlling these fires are significant. The results of this study, specifically the dataset, could be used to estimate terrain accessibility and predict fire development in strategic planning of fire-fighting activities.

Finally, the primary area of use identified by the authors is forest operations internationally. Nevertheless, the dataset, as stated above, would certainly be valuable in the fields of geology, climate research and large-scale planning of forest conservation and management.

Conclusion

Global mapping of the distribution and area of forest land belonging to certain classes of slope has not previously been available. This study reveals that 82 per cent of the worlds´ forests grow on slopes $< 15°$, the distribution of forest between slope classes varies greatly between continents, and between the dominant wood-harvesting countries. The results of this study and the actual raster dataset can be accessed and utilized freely.

Supplementary material

The following supplementary material is available at *Forestry* online: The full, global, raster data containing pixel values of the four slope classes. The raster data can be downloaded in .tiff format (Lundbäck *et al*., 2020).

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Conflict of interest statement

None declared.

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