Article

Optimal harvesting decision paths when timber and water have an economic value in uneven forests

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Appendix A Estimation of up-growth and ingrowth probabilities

Appendix A.1 Estimation transition and survival probabilities

We estimate transition and survival probabilities considering the FORHYCS [1] simulations of annual inventories by tree species, diameter class and year ($y_{ij,t}$). Those predictions only indicate the number of live trees by species (30 in total) height class (15 in total) at the end of every year, and comprise data for the period 1970 to 2015 (46 years in total). On this basis, we reckon average transition, survival and mortality rates, for a group of eight clusters [1].

For the simplest model (with no harvest) [2] we consider that an individual or group of trees that are alive in a size (i.e. diameter) class j at the time $t-1$ ($y_{ij,t-1}$), can either die or move up to the next diameter class (up-growth) in a year, which occurs with the probabilities ($p^m_{ij,t}$) and ($p^u_{ij,t}$), respectively. The number of trees that are alive in a size class j at time t ($y_{ij,t}$), is affected by the number of trees belonging to a size class $j-1$ that move up to class j, which happens with a probability ($p^u_{ij-1,t}$).

$$y_{ij,t-1} \cdot (1 - p^m_{ij,t} - p^u_{ij,t}) + y_{ij-1l,t-1} \cdot p^u_{ij-1l,t} = y_{ij,t}. \tag{A.1}$$

The first term in parenthesis of eq. (A.1) indicates the survival rates in a size class at time t. We base the estimation of those rates on the (predicted) tree inventories over the 46-years period, and we do not observe directly the specific fraction of tree entrances (recruitment or ingrowth) and withdrawals (due to mortality or transition to the next class). Therefore, we estimate the joint value of those rates on the basis of changes in tree inventories by species and size class ($r_{ij,t}$) over two consecutive periods (years):

$$\begin{aligned} r_{ij,t} &= (y_{ij,t} - y_{ij,t-1})/y_{ij,t} \\ r_{ij,t} &= 1 + p^{u+}_{ij-1,t} - p^m_{ij,t} - p^{u-}_{ij,t}. \end{aligned} \tag{A.2}$$

We expect that if $r_{ij,t} < 0$: $1 + p^{u+}_{ij,t} < p^m_{ik,t} + p^{u-}_{ij,t}$, those relative changes are dominated by tree mortality and/or by tree moving up to the upper diameter class. On the contrary, if $r_{ij,t} > 0$: $1 + p^{u+}_{ij,t} > p^m_{ij,t} + p^{u-}_{ij,t}$, we expect forest net growth heads up changes on tree inventories over the period. We cannot discriminate between tree entrances, mortality and other tree withdrawals, in a simplistic way. Therefore, we make some further assumptions to estimate both, tree transition probabilities and mortality. We assume that in case In that case $r_{ij,t} < 0$, the probability of new entrances in a size class j equals zero ($p^{u+}_{ij,t} = 0$). Thus, we account only for the net entrances when the relative change in the number of live trees is positive.

Likewise, we cannot directly observe the fraction of tree withdrawals due to mortality or up-growth. The mortality ratio can be, nonetheless, calculated using Eq. (A2) and the following relationships:

$$\begin{aligned} -p^{u-}_{ij,t} &= p^{u+}_{ij+1,t}. \\ p^m_{ij,t} &= p^{u+}_{ij+1,t} - r_{ik,t}. \\ \text{only if } & r_{ij,t} < 0 \text{ and } r_{ij+1,t} > 0 \end{aligned} \tag{A.3}$$

We quantify the average time interval (τ_{ijk} , in years) needed for moving from one diameter class to the upper one, considering aggregated net tree entrance rates. We assume that the density function of net entrance probabilities follows a normal distribution $N(\mu, \sigma^2)$, and that the average time interval a

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[1] Those clusters are defined according to their altitude above sea level (masl) and orientation (North or South), as indicated in the main text.

[2] TreeMig estimations do not consider harvest, and assume that mortality drives tree withdrawals.

tree remains in a diameter class, corresponds to the time interval half of trees need to moved up to the upper diameter class:

$$\tau_{ij} = \frac{T}{2} \cdot \left(\sum_{t=1}^{\tau_{ij}} \Phi_{ij} \cdot (1 + p_{ij,t}^{u+} - p_{ij,t}^{m} - p_{ij,t}^{u-}) \right)^{-1}, \tag{A.4}$$

where, Φ_{ij} is a binary variable that takes a value of 1 in case $r_{ij,t} > 0$ and a value of 0 if $r_{ij,t} < 0$,.

We further make some additional corrections for those age classes or species with a small number of "observations" for certain size classes. In case, we have information about the time intervals of a number of diameter classes within the same species, we estimate the weighted average time interval of those diameter classes with valid results. In case the number of trees of a forest species is too small to estimate reasonable τ_{ijk} values, we consider the values of the closest species with valid information .

We appraise the fraction of trees that remain alive in a size class j (u_{ij}) and the fraction of live trees that move up to the next size class $j+1$ (q_{ij}) over the period θ. Those parameters are estimated in view of the time τ_{ij} half of the live trees remain in a size class j, their mortality ratio (μ_{ij}) over the time interval θ: $\mu_{ij} = \rho_{ij}^{m} \cdot \theta$, and bearing in mind that those fractions should range between 0 and 1. That is: $0 \leq u_{ij} \leq 1$; $0 \leq q_{ij} \leq 1$; and $0 \leq \mu_{ij} \leq 1$, hence: $u_{ij} + q_{ij} + \theta \cdot \rho_{ij} = 1$[3]:

$$q_{i1} = \begin{cases} 1 - \mu_{ij} & \text{if } \tau_{ij} < \theta \\ (\theta / \tau_{ij}) - \mu_{ij} & \text{if } \tau_{ij} \geq \theta \end{cases} \tag{A.5}$$

$$u_{ij} = (1 - (q_{ij} + \mu_{ij}^{m})) \tag{A.6}$$

Fractions q_{ij} and μ_{ij}^{m} are used to adjust linear and nonlinear functions that relate the up-growth and mortality probabilities with the stand basal area and diameter of the trees, to estimate the survival and transition parameters of Equations (8), (9) and (10) of the main text (see Tables 3 and 4).

Appendix A.2 Estimation of the number recruited trees

The number of trees entering in the smallest diameter class ($R_{i,t}$) every period is obtained from equation (A.2) of the main text. Those entrances are estimated as the difference in the number of trees of the smallest size class: $(y_{i1,t} - y_{i1,t-1})$, corrected by a variable w that accounts for tree withdrawals due to both moves up the next size class (p_{ij}^{u+}) and mortality (p_{ij}^{m}):

$$\begin{gathered} R_{i,t} = y_{i1,t}/(1 + w_i) - y_{i1,t-1} \\ \text{where:} \\ w_i = (\rho_{i1}^{u+} + \rho_{i1}^{m}); \\ \rho_{i1}^{u+} = q_{i1}/\theta. \end{gathered} \tag{A.7}$$

Where q_{i1} represents the fraction of the trees that move up from the smallest diameter class to the subsequent one over the time interval θ. Similarly, variable $R_{i,t}$ is used to estimate the parameters of the tree recruitment function defined by Equation (A.7) of the main text as function of tree density.

Appendix B FORHYCS allometric functions

The FORHYCS simulations provide information about the dynamics of tree height distribution (considering 15 height classes starting from 1.37 to 60 m and in height steps of 4.2 m, except for the first height class, which ranges from 1.37 m to 5.4. The initial value 1.37 is the breast height (equal

[3] Note that μ_{ij} represents the annual mortality probability therefore we multiply this rate by θ

to 4.5 feet), and the diameter estimates are measured from this height on wards. We consider seven diametric classes that range from 0 to more than 70 cm, with intervals of 10 cm. Each class indicates central values, thus a diameter class 5 comprises trees that are 0 cm or higher up to tree with a 10 cm diameter, and so on. The last class comprises tree that are 70 cm o higher. The reason for truncating 70 cm as the last diameter is that higher diameters do not affect timber prices.

The evolution of the diameter at breast height (DBH_{ij}) (in cm), for the species i $(= 1, 2, \cdots, m)$ and height class j $(= 1, 2, \cdots, n)$ can be obtained following an allometric relationship [2]:

$$DBH_{ij} = D_{max} \cdot (1 - \sqrt{\Theta}),$$
$$\Theta = \min\left(1, \max\left(0, \left(1 - \frac{H_j - 1.97}{H_{max,i} - 1.37}\right)\right)\right), \tag{A.8}$$

where: H_j represents the minimum height (in m) of each size class j, while $D_{max,i}$ and $H_{max,i}$ are species-specific parameters indicating maximum DBH and height, respectively.

DBH_{ij} is useful to estimate other relevant allometric data such as the basal area BA_{ij}, total biomass (W_{ij}) or the leaf area (LA_{ij}), for each i species and diameter class j.

The basal area indicates the total cross-sectional area of all stems in a stand. BA_i is measured at breast height for a species i, expressed as per unit of land area (m^2/ha), and estimated as usual as:

$$BA_i = \sum_{j=1}^{n} \left(\frac{\pi \cdot d_{ij}^2}{4} \cdot y_{ij} \right), \tag{A.9}$$

being d_{ij} is the average diameter at breast height (expressed in m), and π the number pi.

On the other hand, the leaf area is calculated considering two-sided area of all tree leaves in the stand, and depends on species-specific parameters and DBH. The following equation is applied to each height class of each species:

$$LA_{ij} = SLA_i \cdot \kappa_{1,i} \cdot DBH_{ij}^{\kappa_{2,i}} \cdot y_{ij} \tag{A.10}$$

where: SLA_i (in m^2 kg^{-1}) is the specific leaf area (foliage area per unit foliage weight), and $\kappa_{1,i}$ (kg cm^{-1}) and $\kappa_{2,i}$ are species-specific allometric parameters relating DBH to the foliage weight. Total stand leaf area is the sum of calculated leaf area for each species/height class corrected by the factor ($s = 10.000 \cdot 2$). This factor is needed and as parameter SLA_i consider the ratio of leaf area to ground area, and that tree data at each plot are referred to one hectare (10.000 m^2), the sub-factor 2 is due to the fact that LAI is defined on the basis of one-sided leaf area.

$$LA_{\text{stand}} = \sum_{j=1}^{n} \cdot \sum_{i=1}^{m} (LA_{ij}) / (10.000 \cdot 2). \tag{A.11}$$

On the other hand, biomass is calculated by individual tree as the sum of foliage and stem weights (in kg m^{-2}), which are in turn defined as function of DBH. Foliage weight (W_{ij}^f) and stem biomass(W_{ij}^s) are calculated as follows:

$$W_{ij}^f = c_{1,i} \cdot \kappa_{1,i} \cdot DBH_{ij}^{\kappa_{2,i}}. \tag{A.12}$$

$$W_{ij}^s = 0.5 \cdot \left((1.441 * 10^-4) \cdot e^{(ln \cdot (DBH_{ij}) \cdot 2.4} \right). \tag{A.13}$$

The factor 0.5 converts stem volume to biomass (kg m^{-2}), so Eq. (A.12) is also used to estimate timber volume. Total biomass (W) and total timber volume (V) are reported in metric tons (t ha^{-1}) and cubic meters (m^3 ha^{-1}) per hectare, respectively, and calculated, considering, in addition, the number of trees by species and height class per hectare.

$$W = \sum_{i=1}^{m} \cdot \sum_{j=1}^{n} \left((W_{ij}^{f} + W_{ij}^{s}) \cdot y_{ij} \right). \tag{A.14}$$

$$V = \sum_{i=1}^{m} \cdot \sum_{j=1}^{n} \left(\frac{W_{ij}^{s}}{0.5} \cdot y_{ij} \right). \tag{A.15}$$

The species specific parameters used to estimate the above referred allometric functions are depicted in Table A.1.

Appendix C Timber and water yield valuation

Appendix C.1 Timber yield and prices

Timber prices were provided by the Swiss Federal Office of Statistics [3], and those correspond to producer prices for raw and unprocessed native woods (including wind-thrown wood), at the forest logging park, without value-added-taxes (VAT). Those are real prices (for year 2014) considering four-month length periods from September 2000 to April 2016 (47 periods) for nine species and different quality classes (see Table 2 of the main text and Table A.2 of this appendix). Available timber price statistics do not cover relevant tree species such as the European larch (*Larix decidua*), Scots pine (*Pinus sylvestris*, Swiss stone pine (*Pinus cembra*). To assess the value of timber assets for Switzerland[4], the Federal Office of Statistics (FSO) used factors that relate the prices of latter species to spruce (*Picea sp*) prices. In case of larch and stone pine, this factor equals 2, and to 1 for the remaining softwood species. While, beech (*Fagus sp.*) is the reference species for other hardwoods and the price factor is set to 1. We have contrasted those factors using the timber prices published every year by the Swiss Wood Industry Association East Regional Office from 2009 and 2016[5].

In that case we have analyzed the historical timber price relationships for round wood prices published by the latter wood industry association; which provides price information for different timber species (spruce, fir, larch and Scots pine among others) and timber quality classes, for what they call the "quartile 4" (from September to December) and occasionally quartile 1 (from January to April). This information was collected from 2009 to 2016. using this data, we have observed that the correction factor depends on the timber quality (for the general qualities classes A to D) and we apply this specific correction factors to estimate larch and Scots pine prices in relation to spruce prices, as they are lower or higher (depending on the quality class) from the correction factors used by the FOS (see Table A.3).

Appendix C.1.1 Surface water yield and valuation

As indicated in the main text, water provisioning services are valued considering drinking water, irrigation and hydro-power net benefits and demands in the Navisence area. Net benefits corresponds to the net returns to water utilities, farmers and hydro-power plants after paying the production factors (labor and manufactures capital). Those benefits are considered *return to natural capital*, which we call *'environmental price'* of water. Those environmental prices are estimated considering irrigation water, drinking water and hydro-power benefits minus their production cost, including capital costs. As the information used to estimate water demand and net benefits is not directly available at the Navisence

[4] [see 4].
[5] Regionalverband Ost und Waldwirtsschaftsverb (Swiss Wood Industry Association East Regional Office), various years. Rundholz Richtpreisempfehlung. Available online: http://www.his-ost.ch [Last accessed 01/11/2016].

area, those variables are estimated using different information and data taken from available statistics and literature, as it is detailed next.

Drinking water demand is estimated considering water consumption by the permanent residents in the three municipalities inside the catchment area: Anniviers, Chippis and Chalais -data for 2015: [5]-, as well as the drinking water demand for tourists and non-permanent residents. Tourism demand is estimated on the basis of the number of tourist nights recorded in those municipalities in 2014 [6], and further considering that hotels comprise only a 29% of total accommodation nights provided in Valais in 2014, which in addition includes holiday residences, for both tourists and non-permanent residents[7]. Water consumption by resident day is estimated as the average individual consumption of water in Switzerland [8]; while tourist night consumption corresponds to the average water use in European countries [9]. Drinking water economic revenues correspond to the average water per household of 12 water utilities in canton Valais in 2015 [10]. Drinking water production costs (including labor, inputs and capital costs) correspond to the average variable Swiss drinking water utilities cost as estimated by [11]. We estimate average drinking water benefits of CHF 1.20 per cubic meter ($\pm$ 0.46) and a production cost of 1.05($\pm$ 0.32) CHF/m^3, thus an environmental price of water ranging from 0.11-0.19 CHF/m^3.

Average demand for water for irrigation is estimated considering water consumption per hectare of agricultural land in the neighboring valley (Crans-Montana-Sierre) estimated by [12], and the total agricultural area in the three municipalities inside the catchment [5].The economic value of irrigation water is estimated considering the gross margins of agriculture in canton Valais per cubic meter of water used. Those gross margins are taken from [13] for annual (wheat, corn, forages, sugar-beet, triticalle and meadows) and perennial (fruit trees and vineyards) crops, and the surface those crops occupy in Valais in 2013 [14]. [13] margins consider organic and non-organic farming, and as those margins present important differences, we further consider that the organic and non- organic farming in Valais are similar as the estimated share (close to 11%: 6.000 farms out of 55.200 farms) of organic farms in Switzerland [15]. We further consider the irrigation cost (including fixed and variable irrigation equipment costs) estimated by [16] for canton Basel-land (790 CHF/ha), which is further detracted from aforementioned gross margins to estimate the net benefits of irrigation water. It is further estimated that 66% of the agricultural land in Valais is irrigated (25.500 ha according to [17], out of about 39.000 agricultural land area in Valais [5]), hence the average irrigation cost is corrected considering this latter share of land. The environmental price of water is estimated considering an average irrigation water use of 827 m^3/ha. This latter figure represents the average irrigation water use gauged by [12] for the Crans-Montana- Sierra area, which amounts 3,021,462 m^3, and the agriculture land area of the 11 municipalities considered in this study: Chermignon, Icogne, Lens, Miège, Mollens, Montana, Randogne, Sierre, St-Léonard, Venthône, and Veyras in 2015 [5]. Estimated water environmental prices range from 2.04 to 4.15 CHF/m^3, considering the range of gross margins provided by [13] for extensive, intensive and organic annual and perennial crops (see Table A.4).

Finally, hydro-power economic values are estimated considering average electricity prices and production costs in Switzerland, as estimated by [18] for a kW/h. The hydro-power revenues and cost further account for the total water used for hydro-power production in Navisence catchment between 2004-2008 (191.6 $\pm$ 190.3 million m^3), and an estimated average production of 650 GWh/year in the central of Navisence [19]. In that case all water used for hydro-power production would have an economic value. On the contrary, we estimate that only 3% of total blue water in the catchment area will have a demand as drinking or agricultural water. In that case, our estimations of the environmental price of forest blue water amounts 0.10 $\pm$ 0.02 CHF per cubic meter (see Table 3 of the main text).

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Supplementary material Tables and Figures

Table A.1. Parameters to estimate diameter and leaf area index by group of species

Class	Group 1	Group 2	Group 3	Group 4	Group 5
SLA_i	6.0	6.0	12.0	12.0	12.0
$\kappa_{1,i}$	0.17	0.23	0.06	0.08	0.10
$\kappa_{2,i}$	1.40	1.56	1.70	1.43	1.43
c_i	0.45	0.45	0.45	0.35	0.35

Source: TreeMig, [20]

Table A.2. Relation between timber classes of the price data base and the diameter classes

Species		Share of timber quality class (%) Diameter class (DBH range in cm)					
		10-19	20-29	30-39	40-49	50-59	≥60
Group 1	L1 2b (25-29) B		90				
	L1 2b (25-29) C		10				
	L1 3 (30-39) B			80			
	L1 3 (30-39) C			10			
	L1 2-4 (25-49) B/ C			10	10		
	L1 4 (40-49) B				80		
	L1 4 (40-49) C				10		
	L1 5-6 (50-69) B (*)				25/50	25/50	
	L1 5-6 (50-69) C (*)				25/50	25/50	
	L3 2-4 (25-69) D					25	25
	Particleboard	50					
	Woodchuck	50					
Group 2	4 (40-49), B, L 3		40	50	70	70	70
	4 (40-49), C, L 3		30	30	20	20	10
	Particleboard	25					
	Long energy wood				10	10	10
	Axed split wood	50	30	20			
	Woodchuck	50					

Notes: Group 1 includes Spruce, Fir, Scots pine, Larch, Swiss Stone pine, Other conifers, while Group 2 includes Beech, Maple, Oak and Ash.

Table A.3. Average price ratios for larch and Scot pine in relation to spruce in Switzerland

Quality class	Ratios of timber prices(1) Larch		Scots pine	
	Mean	Standard deviation	Mean	Standard deviation
Class A	1.93	0.30	1.33	0.04
Class B	1.44	0.63		
Class C	1.14	0.39	0.86(2)	0.20
Class D	0.96	0.07		

Source: *Own elaboration* based on Swiss Wood Industry Association (East Regional Office) data from 2009-2016.
Available online:http//www.his-ost.ch)
(1) Price ratios are estimated in respect to spruce.
(2) There are no significant differences between the ratios estimated for the classes B, C and D.

Table A.4. Gross margins by crop type in Switzerland and agricultural land distribution in canton Valais

Class	Surface Valais		Gross margin CHF/ha			
			Non-bio		Bio	
	ha	%	Min	Max	Min	Max
Annual crops	2,059	5.3				
Wheat	456	1.2	1,613	2,059	2,812	3,188
Corn (grain)	211	0.5	1,123	1,123	3,807	3,807
Corn (forage)	193	0.5	1,271	2,082	3,065	3,141
Rye	37	0.1	1,192	1,225	3,007	3,007
Triticalle	141	0.4	6,950	7,098	6,501	7,047
Potato	85	0.2	2,737	3,244	6,610	6,996
Beetroot	644	1.7	1,086	1,086	3,964	3964
Other annual vegetables	246	0.6	968	1,227	2,947	2,947
Annual berries	47	0.1	53,408	87,097	60,611	86,003
Perennial crops	36,748	94.7				
Fruit trees	2,296	5.9	17,100	17,385	29,376	30,108
Vineyards	4,035	10.4	21,119	26,183	19,375	24,262
Natural meadows	29,063	74.9	-593	-189	-334	-178
Artificial meadows	1,199	3.1	1,526	2,073	1,962	1,962
Other crops	155	0.4				
Total(1)	38,807	100	2,964	3,879	3,831	4,537

Source: *Own elaboration* based on: [5,13].