Prediction of tree age distribution based on survival analysis in natural forests

-a case study of preserved permanent plots in the University of Tokyo Hokkaido Forest, northern Japan-

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Tree mortality and survival analysis of natural forests

- **Tree mortality** is a crucial element of **population dynamics**.
- It is important for the **maintenance of biological and structural diversity** in forested ecosystems.

(Franklinet al 1987; McComb and Lindenmayer 1999)

- **Natural disturbances** produce **structural complexity** in a forest, resulting in deaths of individual trees; this plays a key role in various ecosystem processes and functions.

(Pickett and White 1985)

- Improved predictions of tree mortality allow
  - to project forest development
  - to estimate the economic and habitat values of forest (Price 1989; Hunter 1999)
  - to assess the impact of environmental stresses and disturbances on forests (Kienast 1991)

Estimate tree mortality- plantation vs natural

- Plantation forests – the event is harvesting of stands
- Uneven aged forests- the event is mortality of individual trees
- **The problem is – event of death not happen every time – in uneven aged forests**
- Tree age- enables to predict the mortality of trees accurately

Alternatives

DBH

Dominant height

Basal area

Growth rate completion index

- ✓ Common approaches – to measure tree mortality
- ✓ These can avoid age-based methods

- However, studies focusing on the survival of **uneven aged forests** are **comparatively rare** because of difficulty of measuring tree age.

Why survival analysis on UTHF?

The University of Tokyo Hokkaido Forest (UTHF)

- natural forest management based on selection cutting
- Define as the Stand based Silvicultural Management System (SSMS)

- 10–17% of the stand volume is harvested by single-tree selection at a cutting cycle of 15–20 years
- Remove the defective trees such as diseased, senescent, non-vigorous, and twisted ones.

The productivity of harvested trees can be enhanced by early identification of likely-to-die or decaying trees

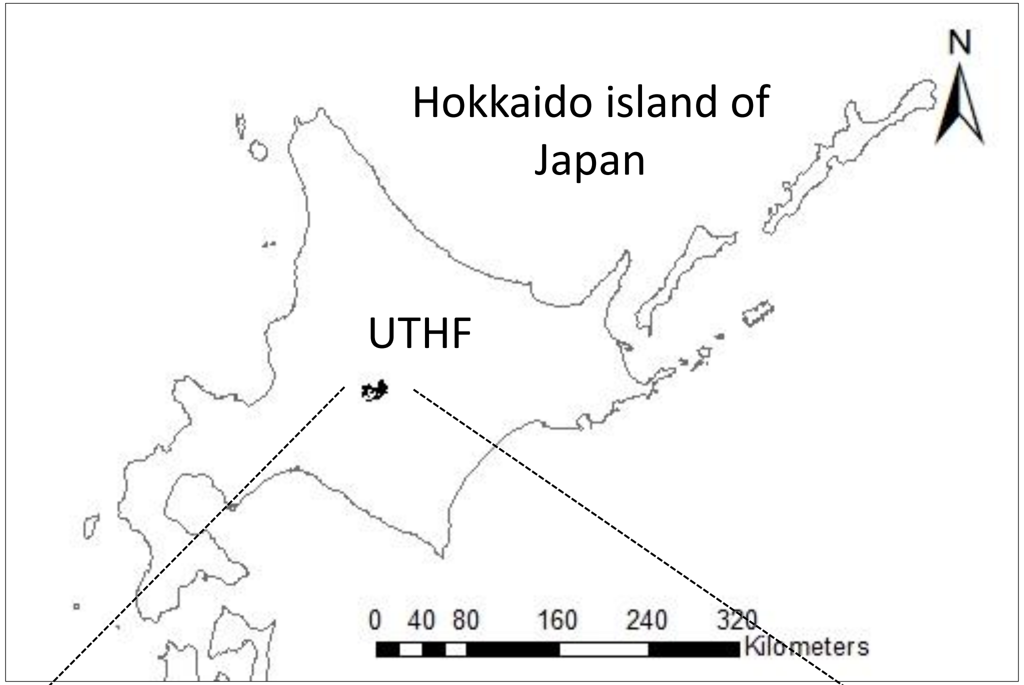
Aim of the study

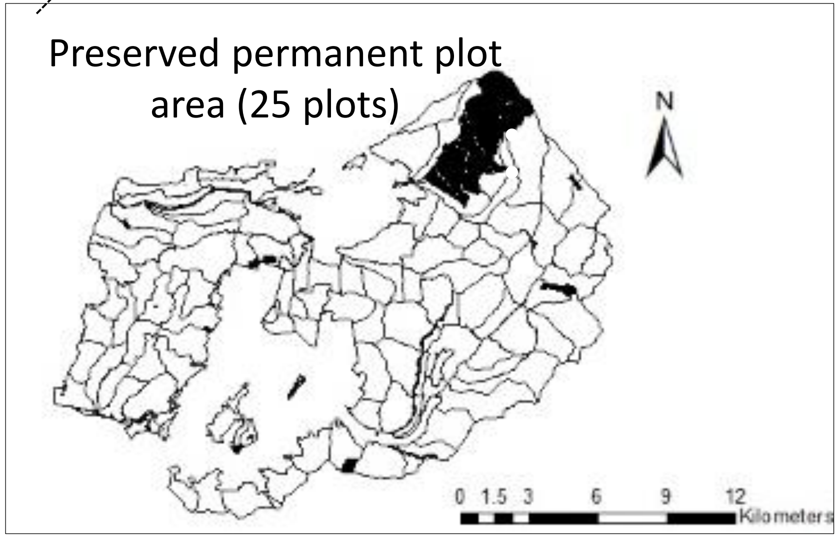
Estimate the survival probabilities of an uneven aged forest stand in northern Japan

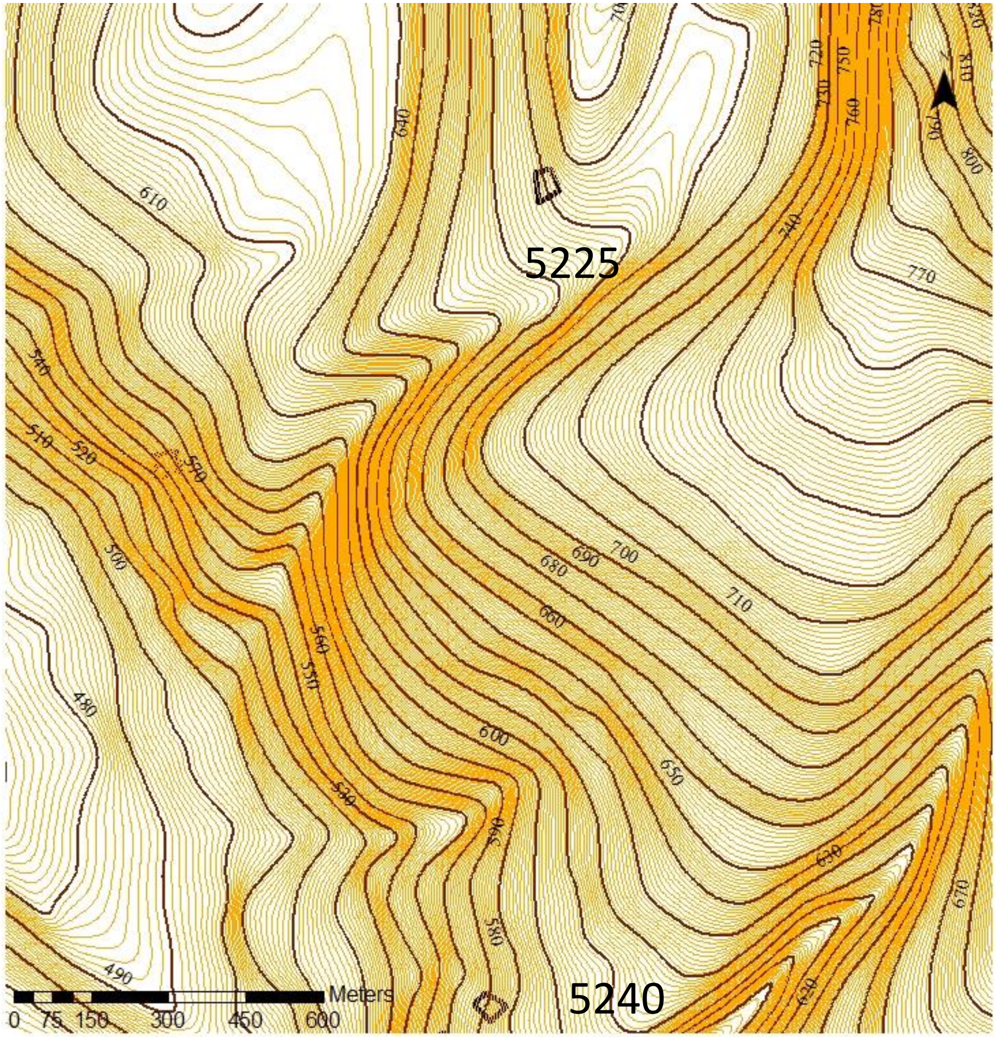
Specific objectives of the study

1. Estimate the mean lifetime of trees based on parametric analysis
2. Prediction of age distribution of living and dead trees

Study area



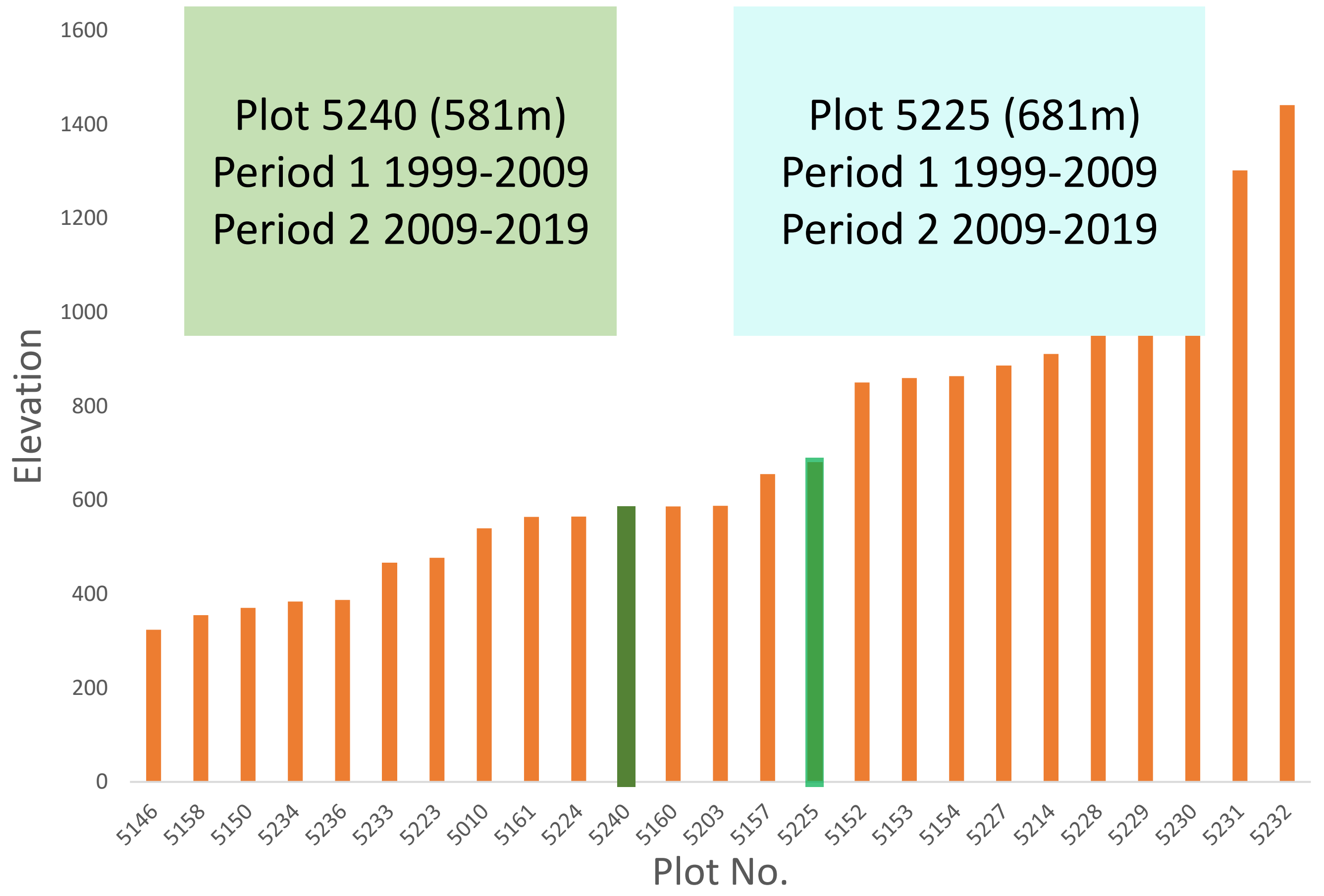




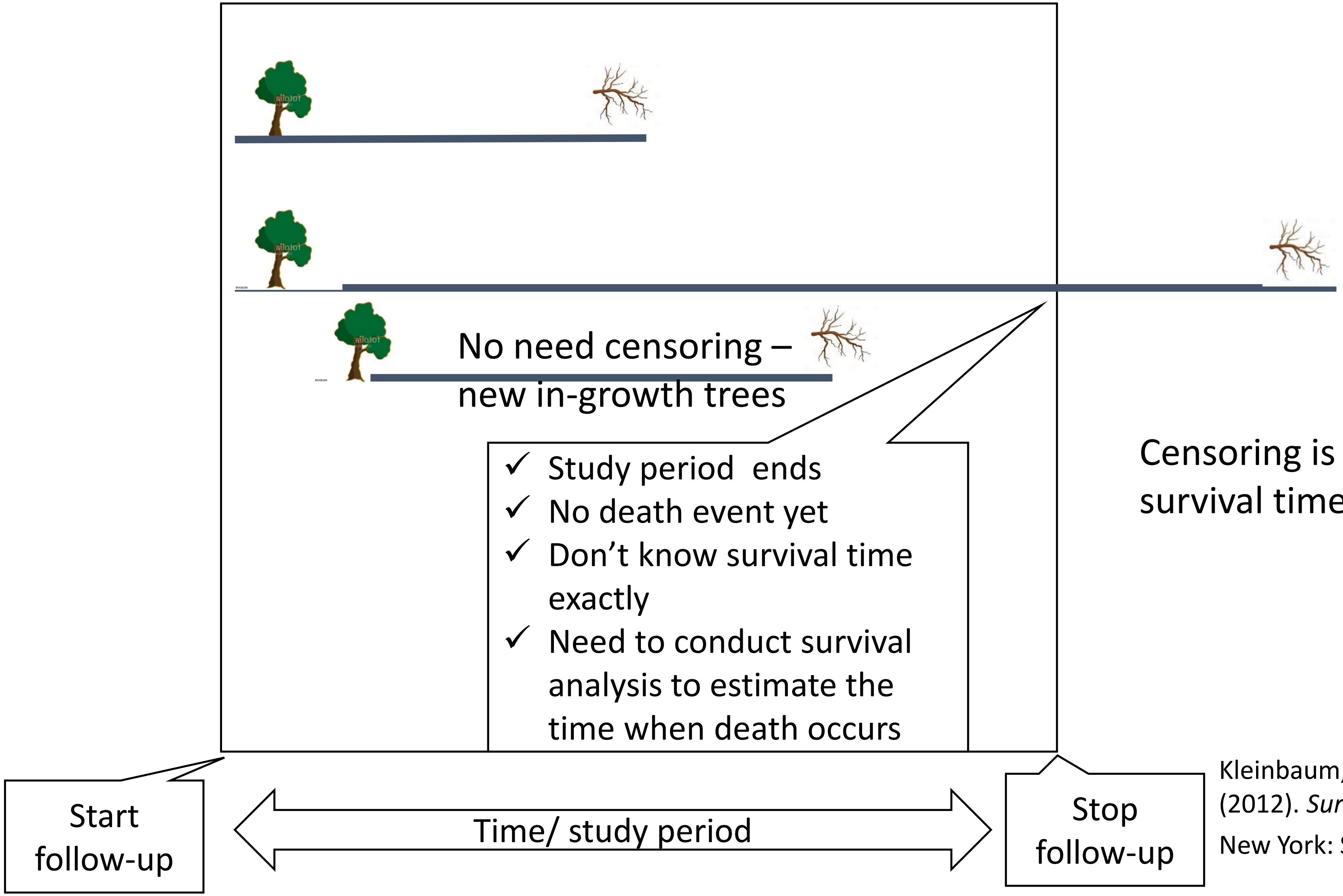
Two preserved permanent plots

Study area cont.

- Main vegetation cover - **uneven-aged mixed forests** with coniferous and broad-leaved tree species
- Why preserved permanent plots for this study ?
  - Availability of **periodical measurements** (growing stock, cutting yield, and mortality)
  - No any management practice
  - Readiness of temporal dynamics
- Typhoon in 2016 – affected to northern part of the UTHF



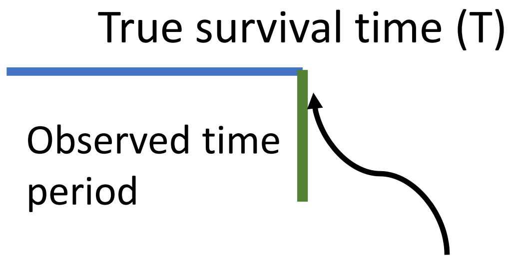
Survival analysis



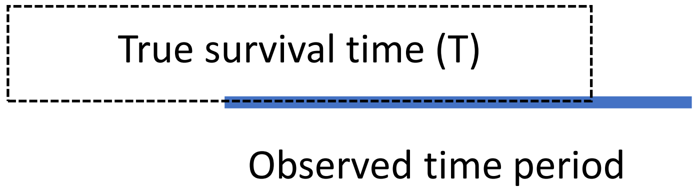
Censoring is done to find the survival time

Kleinbaum, D. G., & Klein, M. (2012). *Survival analysis* (Vol. 3). New York: Springer.

Survival analysis cont.



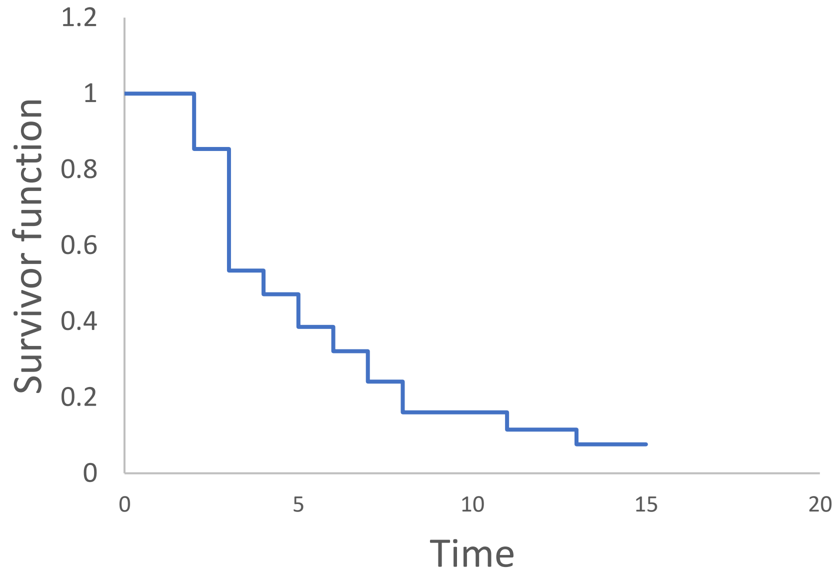
Right censoring- true survival time is equal to or greater than observed survival time



Left truncation - an object is not observed from the start of the study but instead enters the study later

Kaplan Meier survival curve (Kaplan, 1958)

- ✓ Explains how to deal with incomplete observations
- ✓ Use nonparametric tests (not rely on numbers, use rankings/ ranges/ order of sorts)



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Survival analysis cont.

Survival analysis on target trees

- The survival time distribution (1-5 equations) was decided by following Kleinbaum and Klein (2011).
  - ✓ Probability function of trees died at the age class *t* in the observation period;
    $\boldsymbol{Pr(t-1<T\leq t|T>t-1)}$ (1)
    (T represents age after in-growth)
  - ✓ Trees survived age class *t* in the observation period; $\boldsymbol{Pr(T>t|t>t-1)}$ **(2)**
  - ✓ Survival probability $\boldsymbol{(r_t)}$; $\boldsymbol{Pr(T>t-1)=r_t}$ (3)
  - ✓ Mortality probability $\boldsymbol{(q_t)}$; $\boldsymbol{Pr(t-1<T\leq t)=q_t}$ (4)
  - ✓ Mortality rate $\boldsymbol{(p_t)}$; $\boldsymbol{p_t=\frac{q_t}{r_t}}$ (5)
- Likelihood function (*L*) of the observation for whole trees (Hiroshima 2006)

$$L=\prod_t \Pr(t-1<T\leq t|T>t-1)^{d_t}\ \Pr(T>t|T>t-1)^{a_t}\quad(6)$$

ML estimator ;$\log L=0$ $\quad \hat{P}_t=\frac{d_t}{a_t+d_t}$ $\qquad \hat{r}_t=\prod_{k<j}(1-\hat{P}_k)$

$$=\prod_{k<t}\left[1-\frac{d_t}{a_t+d_t}\right]$$

Survival analysis cont.

- Log rank test (Mantel, 1966) - to find the statistical significance between periods and plots

$$Log\ rank\ statistic = (O - E)^2 / Var\ (O - E)$$

Expected No. of deaths (E), Observed No. of deaths (O)

- Parametric analysis
  - ✓Use to assume probability distribution function (PDF) tree mortality ; e.g. **Weibull**
  - ✓Analyze future age distribution of living and dead trees

$$f(T; m, k) = \frac{k}{m^k} T^{k-1} e^{-(\frac{T}{m})^k}$$

PDF parameters of *m* and *k* of the Weibull distribution

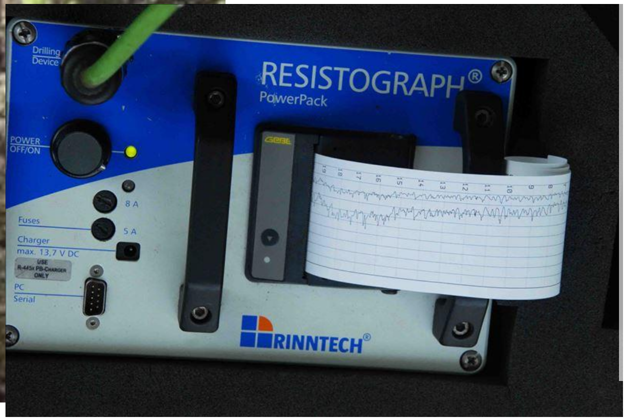
$c_t = (a_{t-1} + d_{t-1})(p_{t-1})$ c_t = No. of dead trees of relevant period

$b_t = (a_{t-1} + d_{t-1})(1 - p_{t-1})$ b_t = No. of dead trees of relevant period

Field data – How to detect tree age?

Trees DBH ≥ 5cm	5225		5240	
	Period 2000-2009	Period 2010-2019	Period 2000-2009	Period 2010-2019
Living trees	192	189	184	187
Dead trees	21	48	34	27
	213	**237**	**218**	**214**

≥ 5 cm DBH trees (Living trees, dead trees, new in-growth trees)



To detect tree age

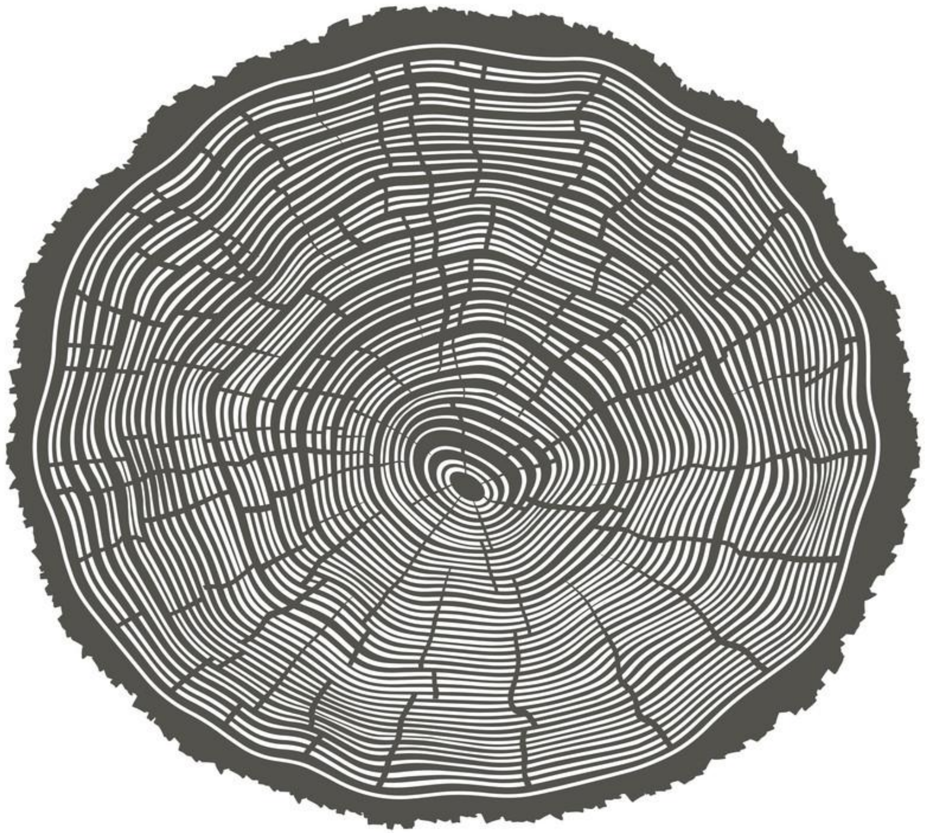
- Conventional destructive methods (e.g. increment borer)
- RESISTOGRAPH

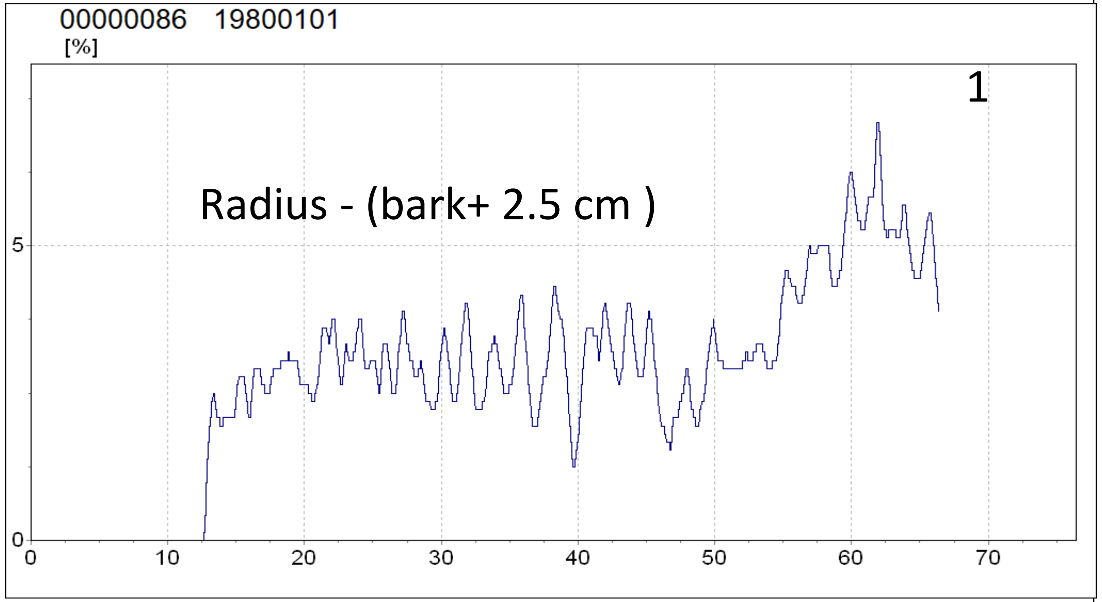
  ↓

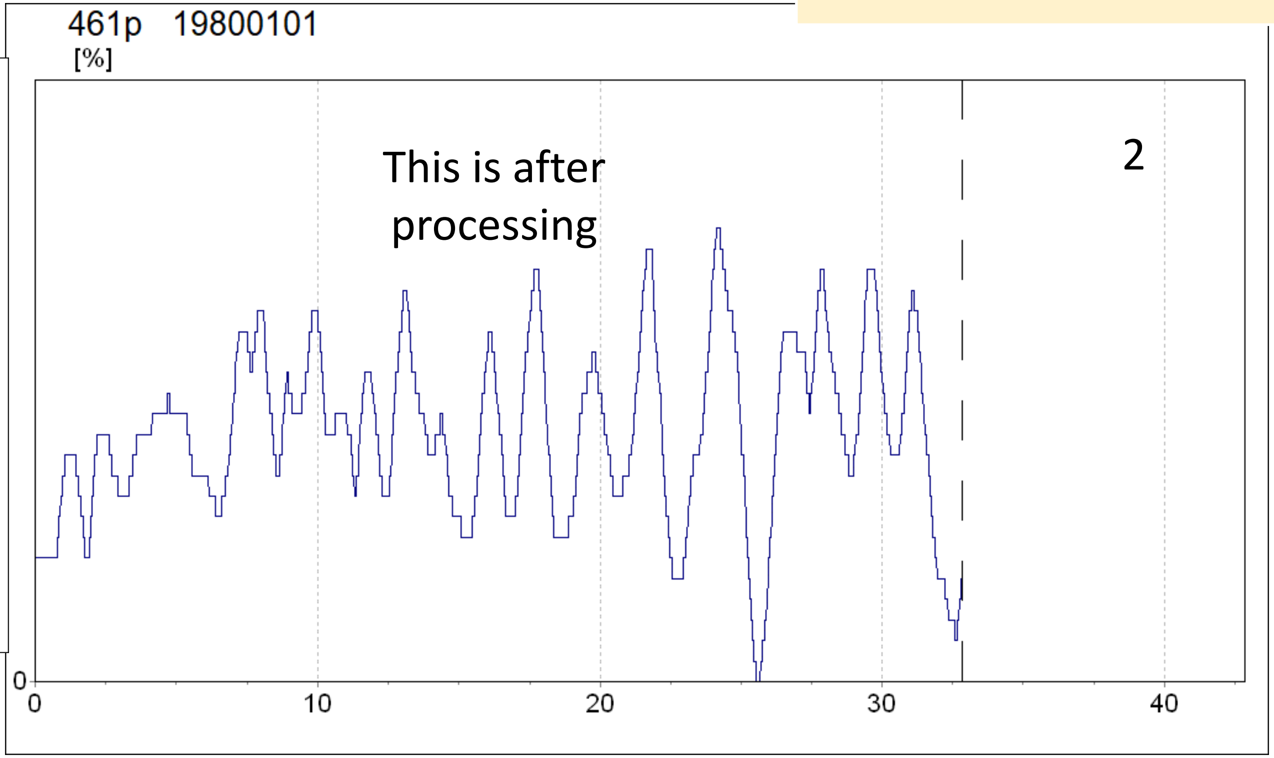
  ✓ Semi-nondestructive method
  ✓ Resistance drilling measurement

Field data cont.

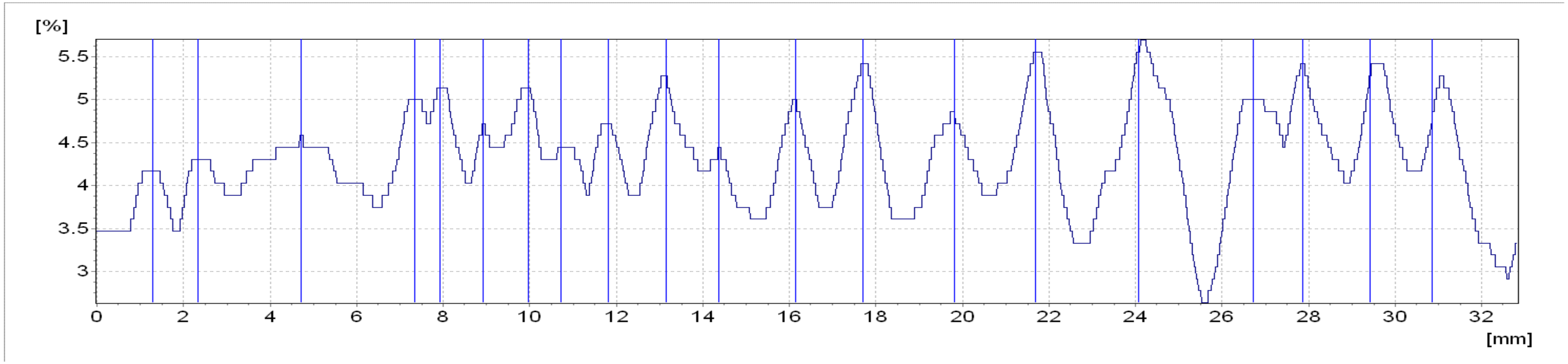
- RESISTOGRAPH measurements
  - ✓ Processing
  - ✓ analyzing
- **DECOM™ -** A specific software to read tree rings
- Tree ring limits are automatically or manually marked by DECOM™.







This is after analyzing



Age class estimation

- Estimations done using simple three-dimensional equations

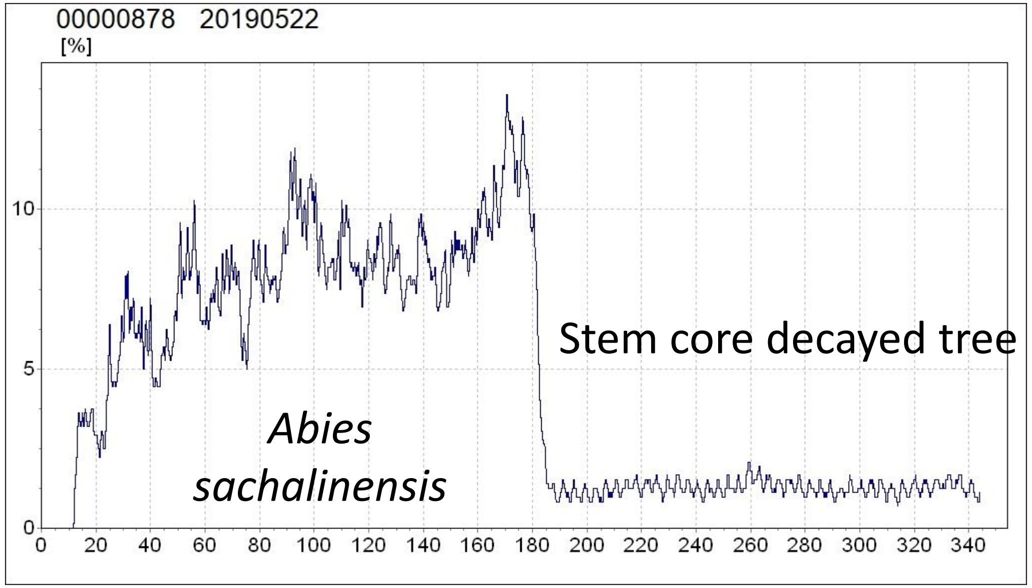
  Plot 5240 – 45/214

  Plot 5225 – 55/237

e.g. *Abies* spp. $y = 0.000005w^2 - 0.0052w^2 + 0.9707w$ (R^2 = 0.6438)

Picea spp. $y = 0.000005w^3 - 0.0032w^2 + 0.9122w$ ($R^2 = 0.8264$)

- Validated with actual wood discs for each species



Inventory data

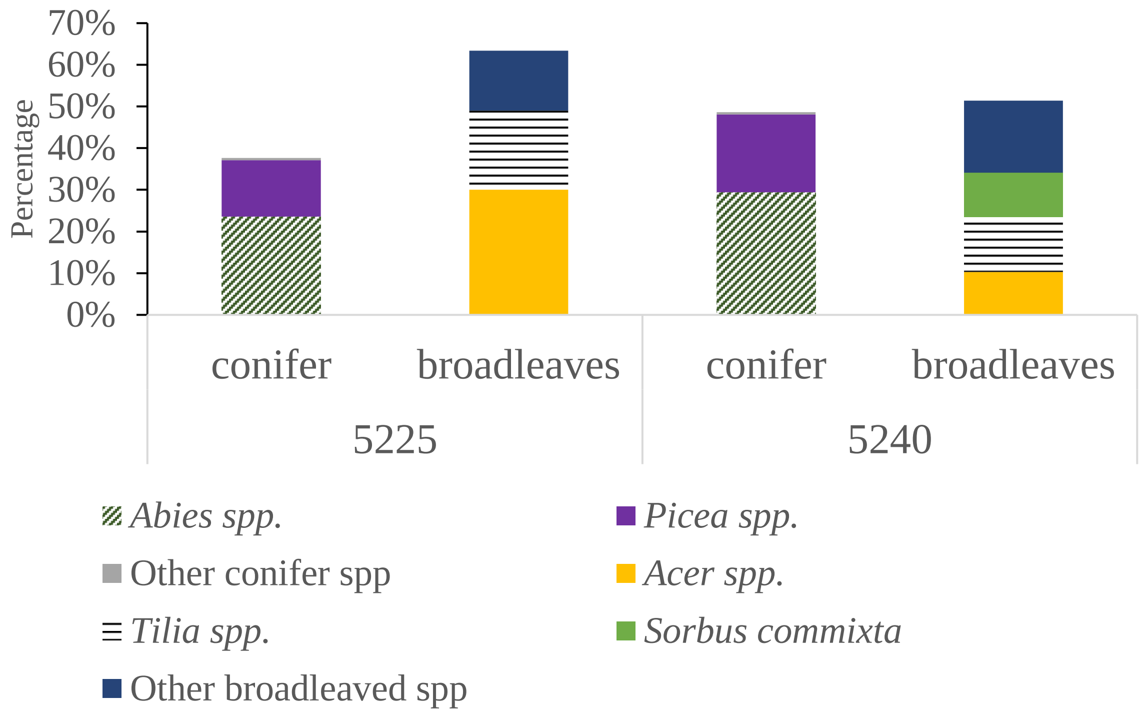
- ✓ Preserved permanent plots,
  - DBH measured at 5 or 10 - year intervals
  - In growth and mortality is recorded
  - Tree characteristics/ defects identified

Tree id	Spp.	tree defects	Wind/ Non wind
7	2	standing dead tree	NW
19	72	standing dead tree, break at root part	W
32	72	tilt	W
38	3	Falling	W
59	72	Falling	W
61	72	Falling	W
62	72	Falling	W
82	3	Falling	W
86	3	standing dead tree	NW
90	72	tilt	W
93	3	standing dead tree	NW
97	2	standing dead tree	NW
106	72	Falling	W
122	2	standing dead tree	NW
134		Falling	W

Tree ID	Species	19740614	Alive/dead	Traits	19790926	Alive/dead	Traits	19840712	Alive/dead	Traits	19890810	Alive/dead	Traits	19940715
1	81	220		0	238		0	262		0	271		0	290
4	2	217		0	235		0	257		0	275		0	292
6	4	241		0	244		0	256		0	257		17	262

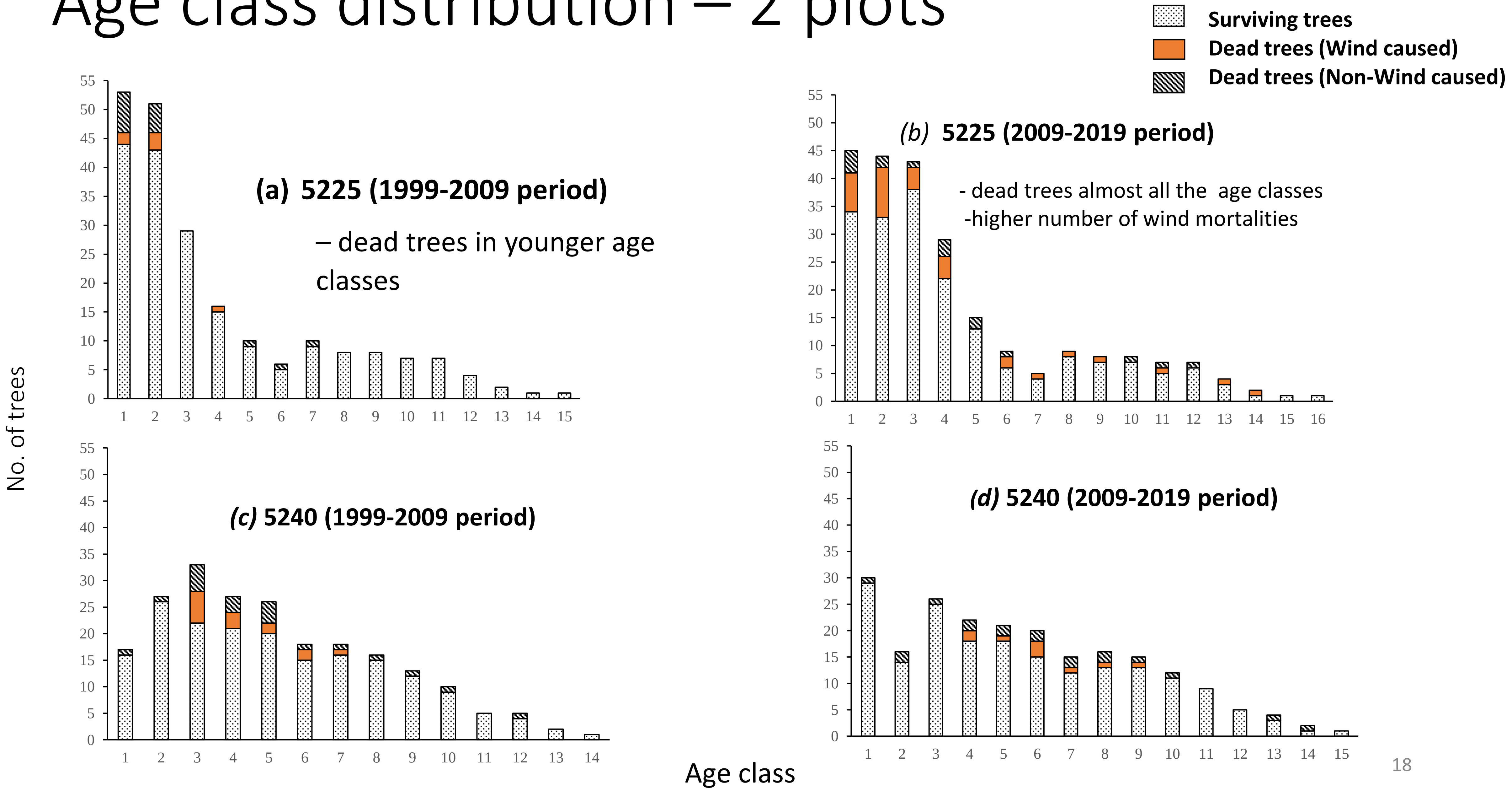
Cause of mortality categorized based on cross-sectional data/field observation

Species composition



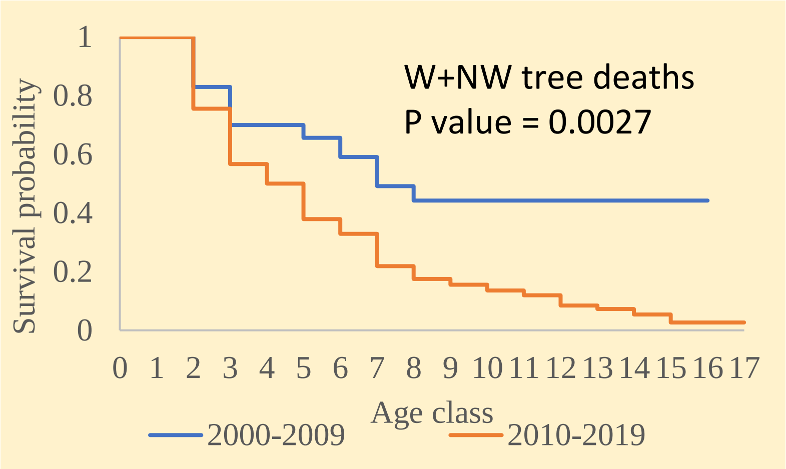
- Observation period 2 (2010-2019)
- 5225 – 237 trees (13 species), major species - *Acer urkrunduense* (29.1%) *Abies sachalinensis* (23.6%)
- 5240 – 214 trees (16 species), major species - *Abies sachalinensis* (29.4 %) *Picea jezoensis* (19.2%)

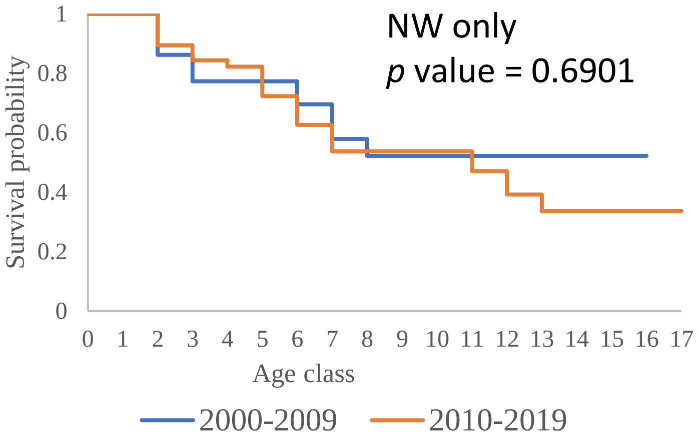
Age class distribution – 2 plots



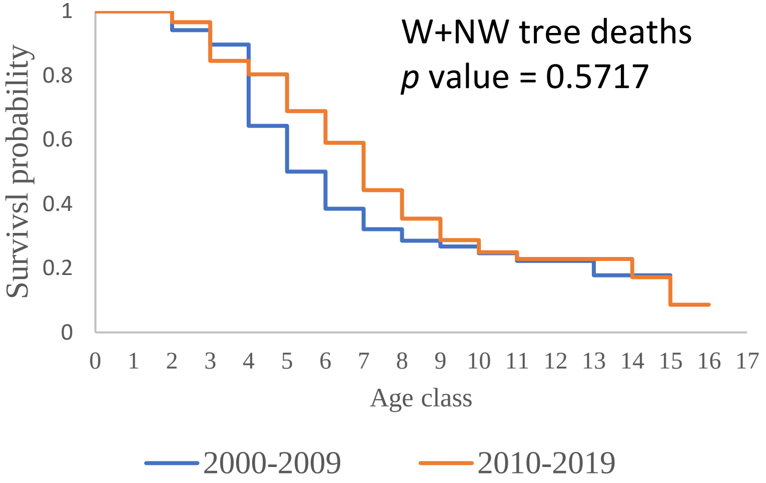
Stand stability between periods

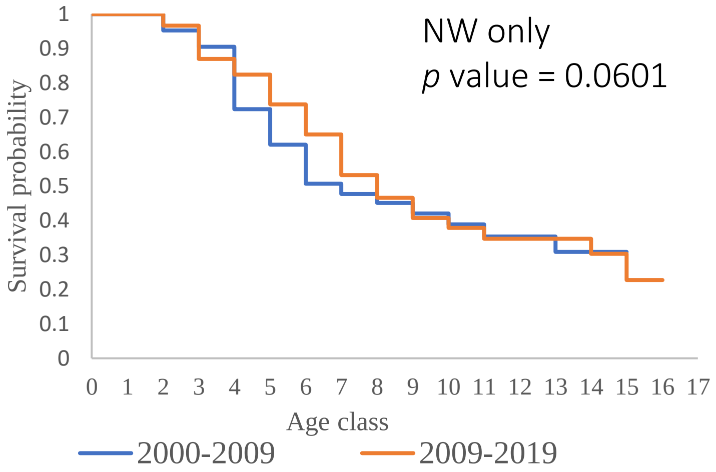
5225





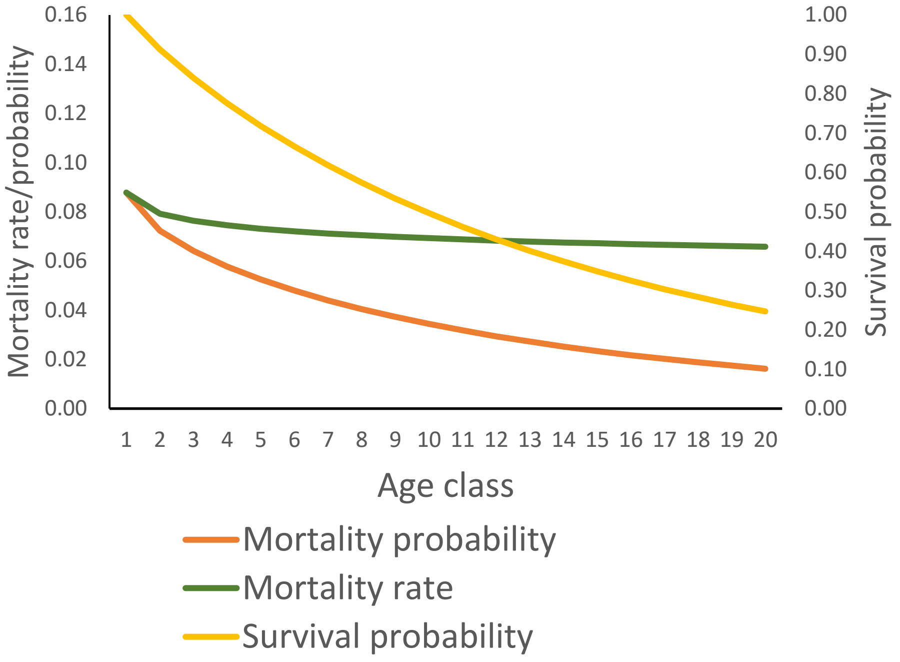
5240

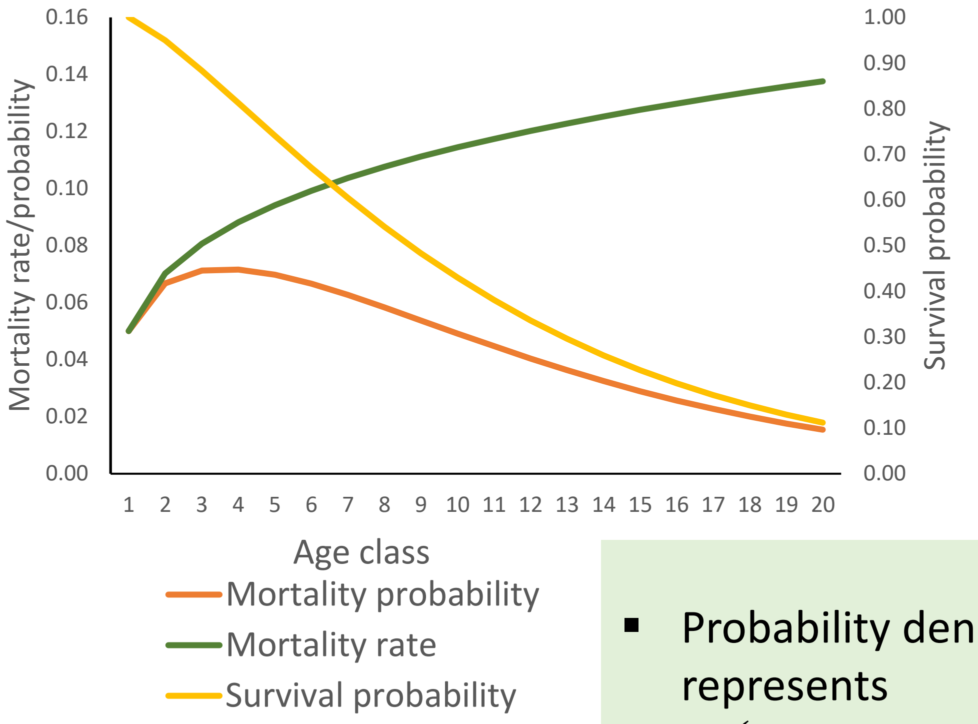




- Only plot 5225 affected with 2016 typhoon during period 2
- Abiotic factors affected on different typhoon effects even with proximity (5240 located on the foot of small plateau – so it could avoid severe wind damage)
- Therefore, Kaplan Meier curves were not stable over the time
- Wind caused deaths were excluded – during further analysis

Parametric analysis – non wind (NW) mortalities of period 2009-2019





- ✓ 5225 period 2 (NW tree deaths)
- ✓ Mean 13.7
- ✓ Variance 219.9
- ✓ Scale parameter – 13.21
- ✓ shape parameter (*k*) – 0.925

- ✓ 5240 period 2 (NW tree deaths)
- ✓ Mean 9.5
- ✓ Variance 56.6
- ✓ Scale parameter – 10.27
- ✓ shape parameter(*k*) – 1.275

- Probability density function represents
  - ✓ Mortality probability (shape and scale parameters)
  - ✓ Mean
  - ✓ Variance
- Form of the survival probability – determined by *k*
- **Mean** value equivalent to **mean lifetime of the stand**

Maturity state of the stand

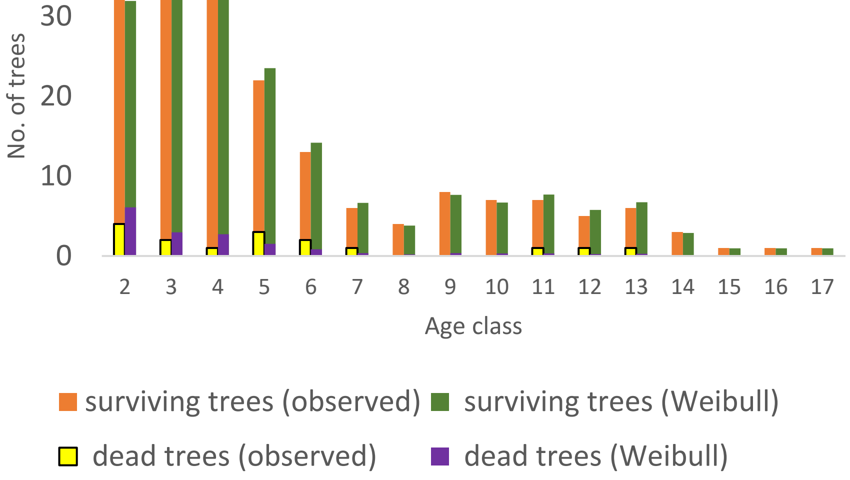
5225		5240	
159	Stand age (years)	149	This is based on tree rings /maximum age of each stand
137	Mean lifetime after ingrowth(years)	95	This is based on parametric (Weibull) estimations
171	Mean biological lifetime (years)	173	This is based on biological lifespan of tree species

Mean lifetime and stand age - near to mean biological lifetime,

- matured state of the stand
- the estimated survival probability is stable over time
- Therefore, future age distribution can be projected based on estimated probabilities

Validation of predicted age class distribution compared with observed one

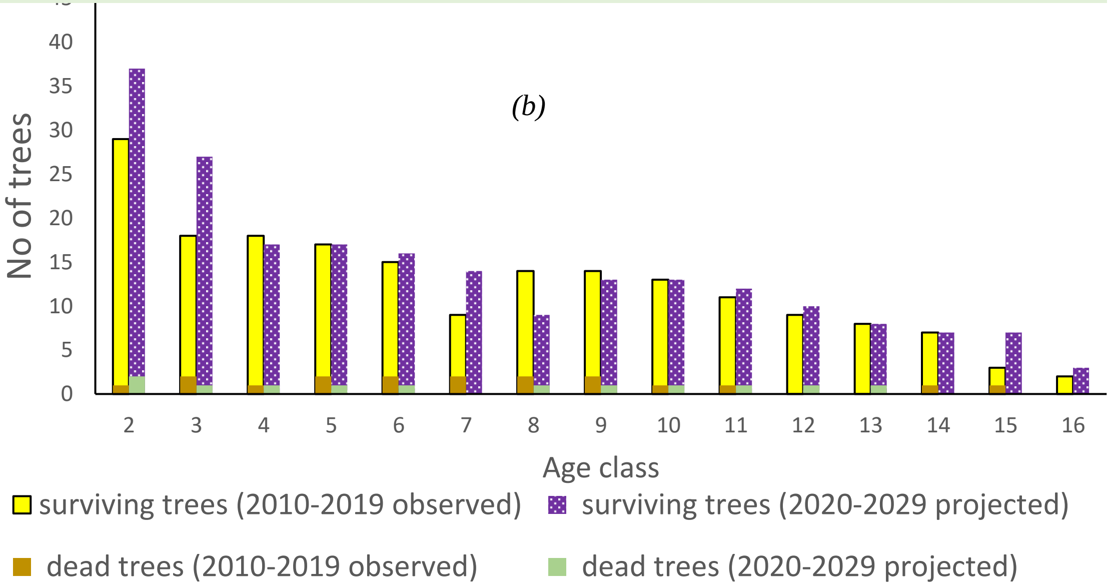
- Period 2010-2019 of 5225 (NW tree deaths)
- Observed and Weibull predictions
- Error ratio
  - ✓ Living trees 1.29 %
  - ✓ Dead trees 16.67 %



- Period 2010-2019 of 5240 (NW tree deaths)
- Observed and Weibull predictions
- Error ratio
  - Living trees 0.63 %
  - Dead trees 0 %

Future predictions

- Forest managers can rely on decision making such as harvesting tree selection based on SSMS
- Facilitate as a harvesting indicator prior to the death of tree
- can be used as site-specific management plans to identify living and dead trees of each age class



Conclusion

- The estimated mean lifetime derived from survival analysis can be used to facilitate management decisions of SSMS of UTHF
- The survival probabilities estimated in this study should be used carefully for long-term predictions of forest dynamics because they do not include the effect of catastrophic disturbances, which can often have significant influences on forests
- In our future work, it is essential to incorporate these variables to enhance survival probability models' practical applicability.

Thank you