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# Year-round production of forest seedlings under LED lamps

## *Biological and energetic implications of indoor cultivation*

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**Abstract**
Hernandez Velasco, M. 2021. Year-round production of forest seedlings under LED lamps. Biological and energetic implications of indoor cultivation. *Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology* 2090. 108 pp. Uppsala: Acta Universitatis Upsaliensis. ISBN 978-91-513-1334-4.

Year-round cultivation of forest seedlings under light emitting diodes (LED) is a technology receiving increased attention from nurseries in the boreal forest regions. In these areas, the climate is characterized by strong seasonal fluctuations, resulting in short vegetation periods with narrow time windows for seedling transplanting and outdoor growth. An indoor pre-cultivation phase under LEDs would offer nurseries the possibility to extend their production throughout the year.

LED lamps present several advantages compared to traditional light sources such as higher efficacies, longer lifetimes and advanced controls. In order to test their feasibility for seedling cultivation, three different LED lamps were compared against fluorescent lights. Biological effects of the light quality were studied through pre-cultivating seedlings of *Picea abies* (L.) Karst. and *Pinus sylvestris* L. under each spectrum in a growth room with controlled conditions. LEDs showed equal or better results than the control also after a forest field trial.

Effects of light quantity were studied for both species using the most promising LED spectrum. Unlike the energy input, which can be considered proportional to the photon flux output, seedling growth exhibited a non-linear behavior with an optimum light intensity depending on the specific requirements of each species.

The year-round cultivation concept enables seedlings to be produced outside of the vegetation period. However, these batches need to be cold stored until the transplanting window opens. Thus, protocols to induce cold hardiness in very young seedlings need to be established. Short-day treatments comparing different temperatures and photoperiods using LED lamps were investigated. Lower temperatures had a significant effect on inducing cold hardiness, especially for *Pinus sylvestris* seedlings.

In contrast to some horticultural crops, which can be cultivated entirely under LEDs, forest seedlings need to be transplanted outdoors at a very young age. This poses a risk for photodamage due to high sunlight intensity and exposure to ultraviolet radiation. Light shock mitigation treatments were investigated by exposing seedlings either to higher LED light intensity, ultraviolet radiation indoors or a transient phase outdoors using shading cloths. Despite some initial stress mitigation, none of the treatments resulted in improved adaptation.

Regardless of how efficient LED lamps become, indoor cultivation will always require electricity. Integrating photovoltaics throughout the nursery could compensate some of this and applying adaptive lighting controls could reduce unnecessary consumption. With proper optimization, these technologies could enable a year-round cultivation under LEDs even in the boreal forest regions.

*Keywords: Picea abies*, *Pinus sylvestris*, year-round cultivation, forest seedlings, LED lamps, light quality, light quantity, daily light integral, adaptive lighting control, greenhouse integrated photovoltaics, agrivoltaics, seedling growth performance, short-day treatments, cold hardiness, light shock stress

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*"The best time to plant a tree was 20 years ago.*
*The second best time is now."*

— *old proverb*

*Dedicated to my family.*

# List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I. Hernandez Velasco, M., Mattsson, A. (2019). Light quality and intensity of light-emitting diodes during pre-cultivation of *Picea abies* (L.) Karst. and *Pinus sylvestris* L. seedlings – impact on growth performance, seedling quality and energy consumption. *Scandinavian Journal of Forest Research*, *34*(3), 159–177. https://doi.org/10.1080/02827581.2019.1578404

II. Hernandez Velasco, M. (2020). Treatments for induction of cold hardiness in *Picea abies* (L.) Karst. and *Pinus sylvestris* L. seedlings pre-cultivated under light-emitting diodes – impact of photoperiod and temperature including energy consumption and seedling quality after cold storage. *Scandinavian Journal of Forest Research*, *35*(1–2), 46–58. https://doi.org/10.1080/02827581.2020.1718199

III. Hernandez Velasco, M., Mattsson, A. (2020). Light shock stress after outdoor sunlight exposure in seedlings of *Picea abies* (L.) Karst. and *Pinus sylvestris* L. pre-cultivated under LEDs – possible mitigation treatments and their energy consumption. *Forests*, *11*(3), 354. https://doi.org/10.3390/f11030354

IV. Hernandez Velasco, M. (2021). Enabling year-round cultivation in the Nordics – agrivoltaics and adaptive LED lighting control of daily light integral. - *in manuscript* https://doi.org/10.20944/preprints202109.0367.v1

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**Conference contributions not appended in the thesis**

Pamidi, S. R., Hernandez Velasco, M. (2014). Reducing the impact of forest plant production – design of a stand-alone PV-hybrid system for powering an innovative forestry incubator. 3811–3814. *29th European Photovoltaic Solar Energy Conference and Exhibition (EUPVSEC)*. 22-26 September 2014; Amsterdam, The Netherlands. https://doi.org/10.4229/EUPVSEC20142014-6AV.5.28

Hernandez Velasco, M., Mattsson, A. (2014). Long night treatment for induction of cold hardiness using artificial lights: effects of photoperiod on seedling storability and energy consumption. Vol.16(5): 379. *Sustaining Forests, Sustaining People: The Role of Research. XXIV IUFRO World Congress*, 5-11 October 2014; Salt Lake City, USA

Hernandez Velasco, M., Kotilainen, T. (2014). New technology for pre-cultivation of forest seedlings under LED lamps – modification of light conditions to mitigate light shock stress after transplanting to open land. *2nd Restoring Forests Conference*. 13-16 October 2014; Lafayette, USA.

Hernandez Velasco, M., & Mattsson, A. (2014). Nuevas tecnologías para el pre-cultivo de plantas forestales – diseño de una incubadora sustentable para minimizar el impacto ambiental. *"Latinoamérica unida en armonia por la sustentabilidad de los recursos forestales". VI Latin American forestry congress.* 20-24 October 2014; Morelia, Mexico.

Hernandez Velasco, M., Mattsson, A. (2015). Outdoor performance of forest seedlings pre-cultivated under artificial lights: effects of the light spectra used for pre-cultivation on the future establishment and development. 20–20. *International Conference on Reforestation Challenges.* 03-06 June 2015; Belgrade, Serbia.

Hernandez Velasco, M., Pamidi, S. R. (2015). Climate control in the production of forest plants: using photovoltaics to power an innovative forestry incubator. 106–111. *6th International Conference in Solar Air-Conditioning*. 24-25 September 2015; Rome, Italy.

Hernandez Velasco, M., Pérez-Mora N., Marras T. (2016). Using hybrid solar photovoltaic + combined heat and power systems (PV+CHP) to enable industrial scale indoor plant cultivation: a feasibility study. *11th ISES EuroSun Conference*, 11-14 October 2016; Mallorca, Spain.

# Personal contributions to the papers

I. Contribution to the design of the experiments; carried out part of the measurements, data analysis and visualizations. Draft preparation and manuscript writing together with co-author.

II. Conceptualization and design of the experiments with inputs from supervisors; carried out measurements, data analysis and visualizations. Draft preparation and manuscript writing with editing and proofreading support from supervisors.

III. Contribution to the conceptualization of the project and design of the experiments; carried out measurements and most part of the data analysis and visualizations. Draft preparation and manuscript writing together with co-author.

IV. Conceptualization of the project and scope definition; data extraction, analysis and visualizations. Draft preparation and manuscript writing with editing and proofreading support from supervisors.

# Contents

# Abbreviations and Symbols

| | |
|---|---|
| A | Surface area [$m^2$] |
| AC | Alternating current |
| AM | Amplitude modulation for dimming control |
| ANOVA | Analysis of variance |
| APV | Agrivoltaics as the co-development of agriculture and photovoltaics in the same space |
| BAPV | Building applied photovoltaic systems, when the solar modules are superimposed but are not part of the building itself |
| BIPV | Building integrated photovoltaic systems, when the solar modules become a part of the building envelope |
| c-Si | crystalline Silicon |
| ChlF | Chlorophyll fluorescence |
| DC | Direct current |
| ddCt | Delta-Delta cycle threshold (ΔΔCt) method to calculate the relative fold gene expression |
| DLI | Daily light integral of photosynthetically active photons on a surface (wavelengths between 400 nm – 700 nm) [$mol \cdot m^{-2} \cdot d^{-1}$] |
| DW | Dry weight [g] |
| E | Energy [J] |
| $E_{el}$ | Electrical energy [J or kWh] |
| $E_{PV}$ | Average energy yield of a photovoltaic system [$kWh \cdot yr^{-1}$] |
| $E_{rel, PV}$ | Relative energy yield of a photovoltaic system [$kWh \cdot kW^{-1} \cdot yr^{-1}$] |
| EC | Electrical conductivity |
| ECMWF | European Centre for Medium-range Weather Forecast |
| EL | Electrolyte leakage |
| EMMs | Estimated marginal means |
| EU | European Union |
| EUR | Euro (currency, €) |
| $f$ | frequency of electromagnetic waves [THz] |
| $F_0$ | Minimum chlorophyll fluorescence for dark-adapted state |
| $F_m$ | Maximum chlorophyll fluorescence after saturating pulse |
| $F_v$ | Variable chlorophyll fluorescence |
| $G_b$ | Beam or direct irradiance on the horizontal plane [$W \cdot m^{-2}$] |
| $G_d$ | Diffuse irradiance on the horizontal plane [$W \cdot m^{-2}$] |
| $G_h$ | Global irradiance on the horizontal plane [$W \cdot m^{-2}$] |

| | |
|---|---|
| $G_\lambda$ | Spectral irradiance with regards to wavelength λ [$W \cdot m^{-2} \cdot nm^{-1}$] |
| GHIPV | Greenhouse integrated photovoltaic system |
| $H_h$ | Global horizontal radiation integrated over a day [$J \cdot m^{-2}$] |
| $\bar{H}_h$ | Monthly average of the daily horizontal radiation [$J \cdot m^{-2} \cdot d^{-1}$] |
| HID | High-intensity discharge lamps |
| HPS | High pressure sodium lamp |
| $I_h$ | Global horizontal radiation integrated over an hour [$J \cdot m^{-2}$] |
| JRC | Joint Research Centre of the European Commission |
| LED | Light-emitting diode |
| MH | Metal-halide lamps |
| mRNA | Messenger ribonucleic acid |
| $P_{fr}$ | Phytochrome active form (far-red light absorbing pigment) |
| $P_r$ | Phytochrome inactive form (red light absorbing pigment) |
| $P_{PV,\ STC}$ | Nominal or peak power of a photovoltaic system measured at standard test conditions [W] |
| PFD | Photon flux density, on a surface [$\mu mol \cdot m^{-2} \cdot s^{-1}$] |
| $PFD_\lambda$ | Spectral photon flux density with regards to wavelength λ [$\mu mol \cdot m^{-2} \cdot s^{-1} \cdot nm^{-1}$] |
| PPE | Photosynthetic photon efficacy of a lamp [$\mu mol \cdot J^{-1}$] |
| PPF | Photosynthetic photon flux, emitted in all directions [$\mu mol \cdot s^{-1}$] |
| PPFD | Photosynthetic photon flux density, on a surface [$\mu mol \cdot m^{-2} \cdot s^{-1}$] |
| PSII | Photosystem II, first protein complex in the light-dependent reactions of photosynthesis |
| PSS | Phytochrome photostationary state |
| PSU | Power supply unit |
| PV | Photovoltaics |
| $PV_R$ | Photovoltaics surface coverage ratio [%] |
| PVGIS | Photovoltaic Geographical Information System |
| PWM | Pulse width modulation for dimming control |
| RGC | Root growth capacity test |
| RH | Relative humidity [%] |
| $RQE_\lambda$ | Relative quantum efficiency for the photosynthesis yield of photons with a given wavelength |
| SD | Short-day treatment |
| SEL | Shoot electrolyte leakage |
| $SEL_{diff,\ T}$ | Shoot electrolyte leakage difference in freezing tests conducted at a target temperature T, usually of -10°C or -25°C [%] |
| SMHI | Swedish Meteorological and Hydrological Institute |
| STC | Standard test conditions for photovoltaic devices |
| $T_a$ | Ambient temperature [°C] |
| UV PFD | Ultraviolet photon flux density [$\mu mol \cdot m^{-2} \cdot s^{-1}$] |
| YPF | Yield photon flux density based on the photosynthetic efficiency weighted by wavelength [$\mu mol \cdot m^{-2} \cdot s^{-1}$] |

## Constants

| | |
|---|---|
| $c$ | Speed of light in vacuum (299792458 $m \cdot s^{-1}$) |
| $h$ | Planck constant ($6.62607015 \times 10^{-34}$ J·s) |
| $N_A$ | Avogadro constant ($6.02214076 \times 10^{23}$ $mol^{-1}$) |
| TSI | Total solar irradiance, defined as the average solar irradiance outside the Earth's atmosphere (1360.8 $W \cdot m^{-2}$) |

## Waveband definitions

| | |
|---|---|
| SW | Shortwave radiation considered between 280 nm – 3000 nm |
| VIS | Visible light, defined as the range between 380 nm – 760 nm |
| PAR | Photosynthetically active radiation, defined as the range between 400 nm – 700 nm |
| UVC | Ultraviolet C radiation, with range between 100 nm – 280 nm |
| UVB | Ultraviolet B radiation, with range between 280 nm – 315 nm |
| UVA | Ultraviolet A radiation, with range between 315 nm – 400 nm |
| B | Blue light, with peak considered at 455 ± 35 nm |
| G | Green light, with peak considered at 535 ± 35 nm |
| R | Red light with peak considered at 660 ± 20 nm |
| FR | Far-red light with peak considered at 730 ± 20 nm |
| IR-A | Near infrared radiation, with range between 760 nm – 1400 nm |

## Greek symbols

| | |
|---|---|
| $\eta_{STC}$ | Efficiency of a photovoltaic device measured at standard test conditions [%] |
| $\lambda$ | Photon wavelength [nm] |
| $\sigma_\lambda$ | Phytochrome action spectra, also known as relative photochemical cross-section |
| $\tau_{h, PAR}$ | Hemispherical transmittance coefficient of photosynthetically active radiation through a greenhouse material [%] |
| $\Phi_\lambda$ | Quantum yield, as the number of events per number of photons absorbed by a system in a radiation-induced process |

# 1 Introduction

Forests cover approximately 35% of the European territory in 2020; accounting for more than 227 million ha (without including the Russian Federation), with around 75% of this area available for wood supply [1]. Since the 1990's the forest area in Europe has increased by almost 10%, producing more wood than what has been harvested. This indicates a sustainable wood supply with growing stocks increasing faster than the felling rates [2].

According to Eurostat statistics, in 2017 forestry and logging activities generated an estimated income of EUR 55.8 billion. Together with this, the downstream activities in wood-based manufacturing, including pulp and paper, produced about EUR 138.6 billion in added value for the European Union (EU). The workforce active in forestry and logging together with those in the wood-based manufacturing sector was estimated to be more than 3.1 million people employed in over 400 000 companies across Europe. This corresponds to almost 20% of the enterprises in the manufacturing sector and 10% of the manufacturing jobs in the EU [2]. Besides timber and fibre, non-wood products like cork, chestnuts, mushrooms, berries and honey from European forests created around EUR 4 billion in revenue together with EUR 500 million for social services such as tourism, hunting and fishing licenses in 2015 [1].

In addition to their significant economic value, forests and other wooded lands can have multiple uses and provide a wide range of essential and invaluable ecosystem services such as biodiversity conservation, water filtering and flow control, soil enrichment, erosion prevention, air quality improvement and climate regulation [3]. Growing forest biomass in Europe captured in average 155 million tonnes of $CO_2$ each year during the period of 2010-2020, which is equivalent to around 10% of the yearly gross greenhouse gas emissions of the EU [1]. Forests also offer society recreational possibilities as well as cultural and aesthetical values, with more than 70% of the European forests accessible to the public [1].

The proportion of forests and other wooded lands in most European countries lays between 30% and 50%. However, countries like Finland, Sweden and Norway with dominantly coniferous forests are well above the EU mean. The forest and other wooded lands cover in these countries reaches 76.2%, 74.5% and 47.1% (23.1, 30.3 and 14.3 million ha) respectively. This together with their sparsely populated areas give their habitants in average access to 3 ha of forest per person [1, 2].

Forest conservation has a long tradition in northern Europe, with more than 100 years of forestry legislation preventing forest destruction, limiting harvest amounts, and ensuring regeneration after felling [4, 5]. Although the first forestry acts were mainly focused on securing future wood supplies, reforms in the past decades have aimed to balance economic, ecological and social goals; adding measures for environmental protection, safeguarding biological diversity as well as promoting natural and cultural sites conservation [6, 7].

Mandatory reforestation after harvest was one of the first requirements included in these legislations and has become a key aspect in sustainable forest management [5]. This obligation can be fulfilled either by facilitating natural regeneration, through direct sowing or by planting of seedlings [8]. Nowadays, planting of conifer seedlings is by far the most used regeneration method in the region. To satisfy the demand, forest nurseries in Norway, Finland and Sweden produce yearly between 500 and 600 million seedlings, being the dominant species cultivated Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.) (see Figure 1.1) [9–11].

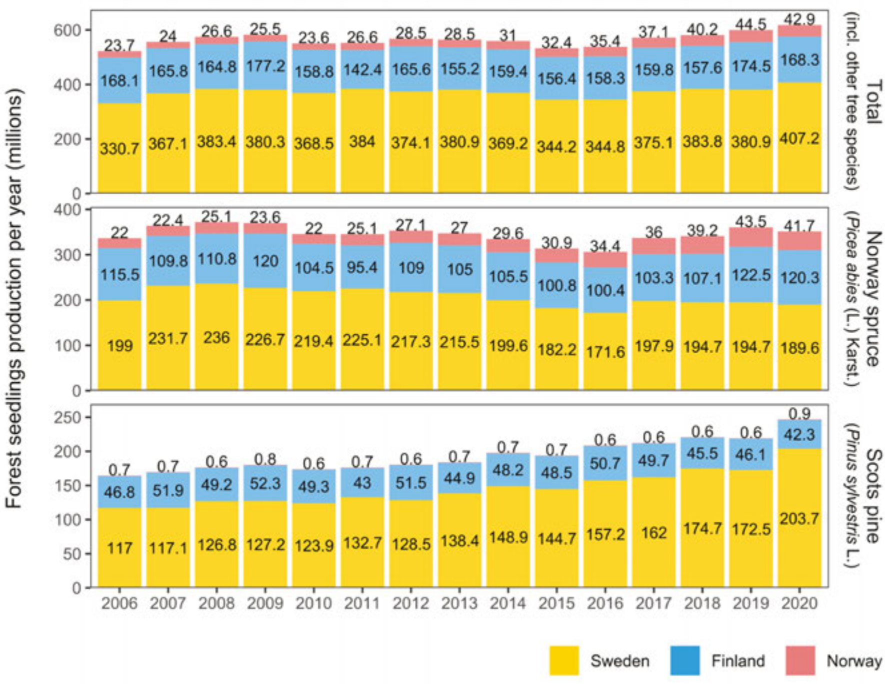



Figure 1.1: Yearly production of forest seedlings from 2006 to 2020 in Norway [9], Finland [10] and Sweden [11]. Total amounts including all reported tree species (top panel) and separate panels only for Norway spruce and Scots pine seedlings.

Forest nurseries in northern Europe started producing containerized seedlings in the early 1970's and the system gained rapid popularity [12, 13]. However, the transition from bare root stock to containerized seedlings was not simple and involved extensive and repeated adjustments of the traditional methods in order to consider for the effects of the biological and technological interactions [14, 15]. In recent years, containerized seedlings account for more than 80% of the stock production [11, 13, 16].

Several decades after the introduction of containerized seedlings, forest companies and research institutes continue to look into new technological improvements [17]. Among some of the new developments are the use of much smaller containers during a pre-cultivation stage to produce "mini-plug" seedlings that can be later transplanted to a final container [18, 19] or directly into the field to possibly reduce the chances of weevil damage [20–23].

Reducing the container volume and increasing seedling density also allow for a better use of the resources in the cultivation area, which in northern latitudes can be high energy demanding due to artificial lighting and heating requirements [24–27]. This could decrease the seedling production costs while opening the possibility for other complementary technologies such as better packaging methods and mechanized planting [28, 29].

Often new developments in forest nurseries come from observing other similar fields such as horticulture [30]. That is the case with the introduction of light-emitting diodes (LED) lamps for cultivating forest seedlings [31–33]. The LED technology as a light source for plant growth has several advantages such as potential reduction in electricity consumption, longer lifetime, lower radiative heat emission, high energy-conversion efficiency, adjustable light intensity and customizable spectra [34–36]. Although the use of LED lamps in horticulture has rapidly established and there is plenty of research available [37–44], there are still relatively few studies conducted on tree species for the boreal forest region [45–52].

The aim of this thesis is to further examine the implementation of LED lights in forest nurseries of the boreal region focusing on a year-round cultivation concept for containerized seedlings. These new growth protocols include an indoor pre-cultivation phase at high container density using LEDs as sole source of photosynthetic light; continued by a transplanting stage into a larger container for further growth in greenhouse or at outdoor conditions.

Within this new concept, the following aspects were evaluated:

- Seedling response regarding LED light quality and intensity.
- Treatments for induction of cold hardiness during pre-cultivation.
- Treatments for mitigation of light shock stress after transplanting.
- Energy demand for lighting and possible optimizations.

## 1.1 Scope and thesis overview

The present work was made as an effort to contribute to the current understanding and facilitate the adoption of LEDs as cultivation light sources in forest nurseries of the boreal region, specifically in Sweden, Norway and Finland. The research was limited to seedlings of the main two conifer tree species commercially cultivated in this region, which are Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.). Focusing mainly on treatment effects within each species rather that comparing between them.

As a general goal in the studies, the seedlings cultivated under LEDs should not suffer any detriment in their quality attributes and thus be able to perform at the same level (at the nursery and in the field) as those seedlings cultivated under traditional light sources such as fluorescent lamps. Should this be the case, the benefits of a year-round production concept using LED lights would translate into an increased annual yield of forest seedlings at equal or higher quality levels but with a lower relative energy requirement for lighting.

The appended papers present a combination of biological and technological assessments that address particular research questions at selected cultivation phases (see Figure 1.2). They follow a common framework that consisted of:

- estimating the limitations of current nursery practices and possible improvements when using LEDs as light source for plant growth;
- adapting the existing methods at that particular cultivation stage in order to integrate an alternative solution based on LED lighting;
- implementing the new approach in a controlled environment with conditions as close as possible to those in an actual forest nursery;
- assessing the seedlings' biological response as well as the electricity demand implications when adopting the new technology.

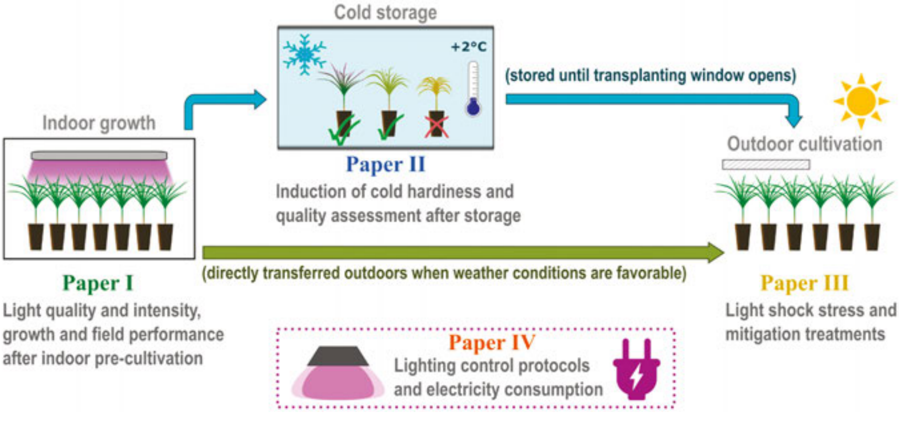



Figure 1.2: Contribution of the appended papers at different stages within the novel concept for year-round cultivation of forest seedlings in the boreal forest region.

The content of the appended papers can be briefly summarized as follows:

- Paper I focuses on the feasibility of using LED lighting for the pre-cultivation of forest seedlings. Different light qualities were assessed based on the seedlings' growth performance at the nursery and during a three-year forest field trial. Three LED luminaires with different spectra were compared against traditional fluorescent lamps. Since LEDs are capable of being dimmed, the impact of the light intensity was evaluated considering both biological and energetic implications.

- Paper II targets the critical cultivation stage of inducing cold hardiness in young forest seedlings that need to be stored at low temperature until the weather conditions are favourable for outdoor growth. The combinations of two short-day photoperiods (5 h or 8 h) at three different temperatures (5°C, 10°C or 20°C) were applied during five weeks. The effectiveness of the treatments was evaluated using different storability assessment methods. Finally, the vitality of the seedlings was measured after three months of cold storage at +2°C.

- Paper III investigates the potential for light shock stress on seedlings pre-cultivated solely under LED lamps upon transplanting directly to sunlight exposure. In contrast to most horticultural crops, indoor growth represents just a small fraction of the long lifetime of a tree. Thus, forest seedlings must be able to cope with the transplant stress and adapt quickly to outdoor light conditions which can differ greatly in spectra and intensity. The effects of the light shock stress, potential risks for poor seedling quality as well as possible mitigations treatments were investigated. These consisted of higher light intensity or exposure to ultraviolet (UV) radiation during indoor pre-cultivation; along with a transient phase outdoors using a shading cloth during the first days.

- Paper IV studies the possibility of incorporating LED lamps in the year-round concept from an energy requirements perspective. It considers the light quantity required for cultivation, either as sole-source or in a greenhouse as supplementary lighting additional to sunlight. Using satellite data, the monthly available photosynthetic light levels and ambient temperatures for the north-European region were estimated. The energy requirements for lighting were calculated assuming different lamp efficacies and two lighting control protocols (on-off or adaptive control) were compared. Finally, the potential for integrating photovoltaics as an alternative to offset some of the electricity consumption was evaluated.

Due to the close and complex interactions between the environmental factors and the biological response of the seedlings, each of the studies focused only on some specific parameters of a particular cultivation phase. Figure 1.3 shows a schematic of the cultivation stage that they were focusing on, the different environmental variables that were modified in each experiment, and the parameters that were adjusted during the energy calculations.

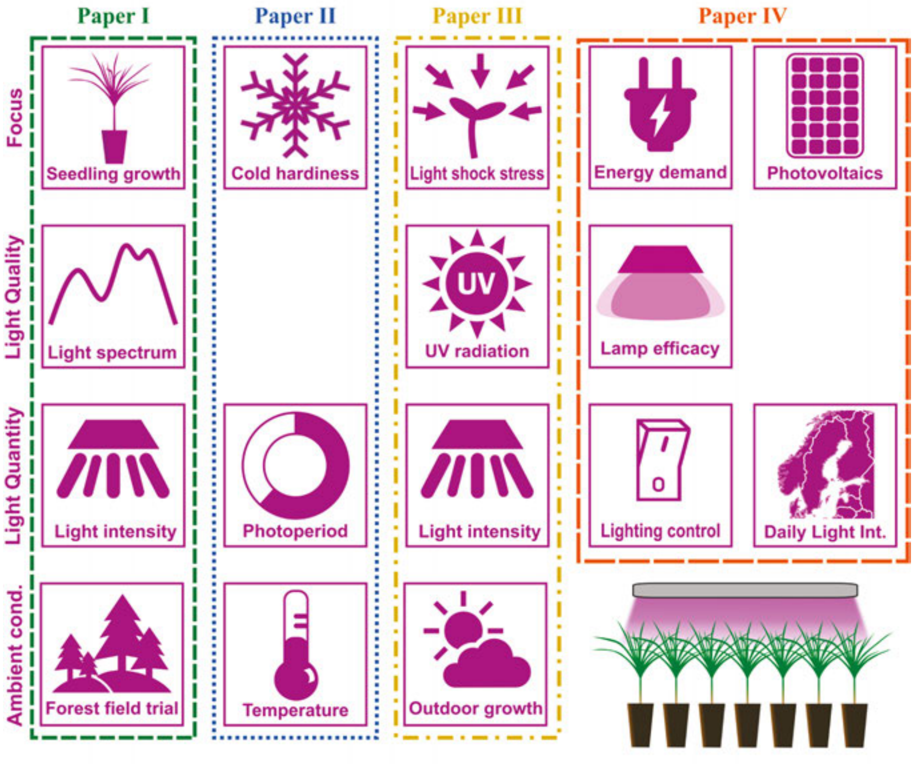



Figure 1.3: Schematic of the different parameters investigated in each of the papers as well as their scope within the development of the year-round cultivation concept.

# 2 Background

Understanding the role of light in seedling development is crucial for implementing the proper lighting regime during cultivation. Although strictly speaking the word ‘light’ refers to the portion of the electromagnetic spectrum that is visible to human eyes; for application purposes and in everyday speech the term light is often used interchangeably with the term radiation [53].

In radiometry, when radiant energy or *radiation* (measured in Joules, J) is considered to be emitted, transmitted or absorbed per unit of time, it is called a *radiant flux* or radiant power (measured in $W = J{\cdot}s^{-1}$). A radiant flux incident over a unit surface area (expressed in $W{\cdot}m^{-2} = J{\cdot}s^{-1}{\cdot}m^{-2}$) is thus called *radiant flux density*. For plane surfaces, a radiant flux density can also be known as *irradiance* (with symbol G). Finally, if an irradiance is integrated over a period of time, is called radiant exposure or *irradiation* (with symbol H, measured in $J{\cdot}m^{-2}$). All of these terms can be expressed as spectral quantities with values per wavelength  λ) or frequency (*f*) if the spectrum is known [54–56].

Electromagnetic radiation is actually formed by two waves, one electrical and one magnetic, oscillating perpendicularly to the direction of propagation as well as to each other. The speed of these waves depends on the medium; in vacuum, all radiant energy travels at the same speed: *c*. This is a universal physical constant defined exactly as: $c = \lambda f = 299792458\ m{\cdot}s^{-1}$ [57].

Due to its dual nature, electromagnetic radiation behaves as a wave and as particle at the same time. It propagates, refracts and causes interference as a wave; yet, when radiation interacts with matter it acts as discrete indivisible particles or quanta called photons [58, 59]. The energy of a photon with a particular wavelength ($E_\lambda$) can be calculated using *Planck-Einstein’s* relation (Equation 1), where *h* is Planck constant ($6.62607015{\times}10^{-34}\ J{\cdot}s$) [57, 60]:

$$E_\lambda = \frac{hc}{\lambda} = hf \tag{1}$$

This inverse relation between the energy of a photon and its wavelength means that radiation with short wavelength, for example within the UVA waveband (315 nm – 400 nm), has more energy per photon than radiation with longer wavelengths such a near infrared (IR-A, between 760 nm – 1400 nm).

The *Stark-Einstein* law of photoequivalence states that when radiation of moderate intensity is transformed into other forms of energy through a photoelectrochemical process; for every photon absorbed only one atom or molecule can be activated [61]. In most cases, it is more practical to consider the amount of substance rather than individual molecules.

The photochemical equivalence law can be thus summarized as: one mole of photons can maximum excite one mole of electrons. A mole of photons or 'mole-quantum' is known as the *photochemical equivalent* [55]. Using Avogadro constant ($N_A = 6.02214076\times10^{23}$ mol$^{-1}$) in Equation 1 it is possible to calculate the energy per micromole of photons of a particular wavelength:

$$E_{mol,\lambda} = \frac{N_A hc}{\lambda} \quad \Rightarrow \quad G_\lambda \approx \frac{PFD_\lambda \cdot (119.63\, J \cdot nm \cdot \mu mol^{-1})}{\lambda_{nm}} \tag{2}$$

Using the values of the physical constants ($N_A hc$) and adjusting the units in Equation 2, values for spectral irradiance ($G_\lambda$, W·m$^{-2}$) can be converted to spectral photon flux density ($PFD_\lambda$, µmol·m$^{-2}$·s$^{-1}$·nm$^{-1}$) (see Figure 2.1).

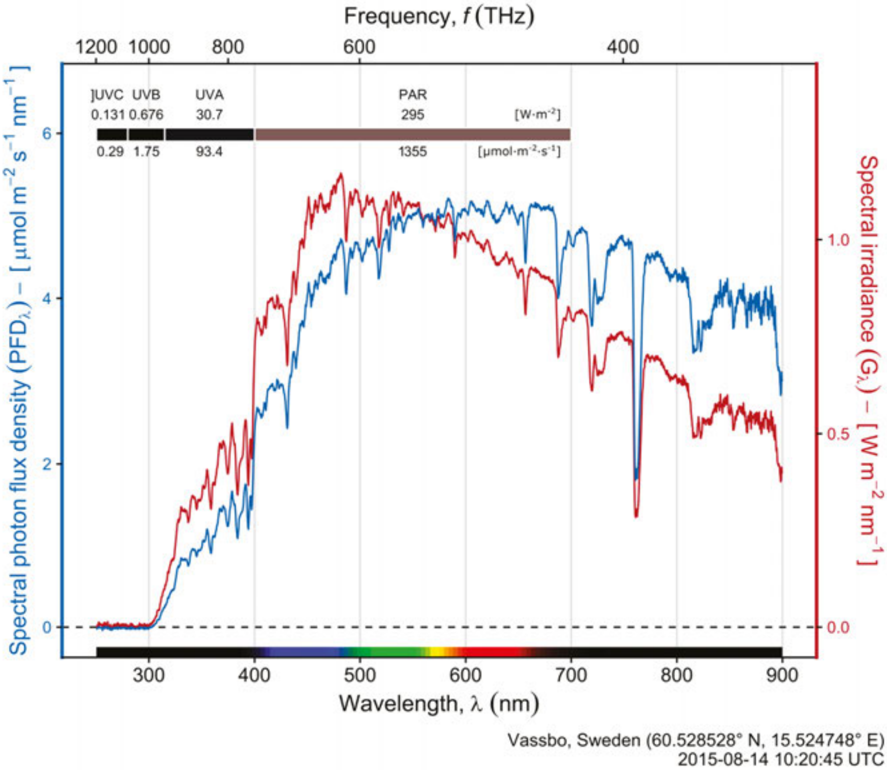



Figure 2.1: Solar spectrum at noon on a clear sky day measured at the research station of Dalarna University in Vassbo, Sweden (60.528° N, 15.524° E). The values are shown both as spectral photon flux density ($PFD_\lambda$, µmol·m$^{-2}$·s$^{-1}$·nm$^{-1}$) and spectral irradiance ($G_\lambda$, W·m$^{-2}$·nm$^{-1}$) as well as a summary for some relevant wavebands.

## 2.1 Light and plant development

The Sun emits energy which arrives to the Earth in the form of shortwave (SW) electromagnetic radiation, with wavelengths ranging roughly between 280 nm to 3000 nm [56]. Outside of the atmosphere, recent measurements estimate the average total solar irradiance (TSI) on a surface perpendicular to the solar rays to be close to 1360.8 $W \cdot m^{-2}$ [62] (slightly less than the traditional 'solar constant' considered to be 1367 $W \cdot m^{-2}$ [60, 63]).

However, only around 75% of this irradiance reaches the surface. As the SW passes through the atmosphere, it is attenuated by the absorption and scattering of air molecules, clouds and dust particles [56]. Practically all of the UVC radiation (in the range of 100 nm – 280 nm) as well as a large proportion of the UVB radiation (in the range of 280 nm – 315 nm) is absorbed by the ozone ($O_3$) in the atmosphere before reaching the ground. Other gas molecules, particularly carbon dioxide ($CO_2$), and water vapor ($H_2O$) present very high absorption regions in parts of the IR-A region [64, 65].

Plants have evolved around sunlight, creating intricate processes like photosynthesis which allows them to harvest the radiation and convert it into chemical energy [54]. According to *Grotthuss–Draper* law of photochemical activation, before these reactions can occur, the radiation must be first absorbed. Hence, plants developed special molecules called pigments, capable of absorbing photons, being chlorophyll the most important of them. Accessory pigments such as flavonoids, carotenes and xanthophylls also play an important role, protecting the cells against UV radiation that carries high-energy levels as well as helping collect photons of wavelengths that chlorophyll is not able to absorb. Following *Stark-Einstein* law, only one pigment molecule can be activated per photon absorbed, so the energy has to be transferred along the photosystem through mechanisms such as fluorescence resonance until it reaches the reaction center [55, 66].

Photosynthesis is a complex process, depending on multiple factors and consisting of several steps (roughly 23), including light-dependent and light-independent reactions [36, 54]. In theory, approximately 10 photons would be needed to fix one molecule of $CO_2$ into carbohydrate (equivalent to 0.1 mol of $CO_2$ per mol of absorbed photons for C3 plants) [67]. This photon-weighted efficacy is called the quantum yield ($\Phi$); defined as the number of events per number of photons absorbed by the system in a radiation-induced process [68].

In reality, photosynthesis can have a considerably lower output depending on the environment, the plant conditions and the spectrum of the radiation [67]. For a variety of plant species, when doing short-term measurements and applying monochromatic light, the average maximum $\Phi_\lambda$ ranges between 0.07-0.08 mol of $CO_2$ per mol of absorbed photons [69–72].

The degree in which a radiation-induced process is influenced by a photon of a certain wavelength is referred to as its *spectral response*. Depending on the mechanism, sometimes this spectral response is calculated with respect to the $PFD_\lambda$ (e.g., photon-weighted photosynthetic efficacy). In other cases, the spectral response is based on the incident $G_\lambda$ for example, when estimating the sensitivity of human eyes to different intensities of visible light (VIS, 380 nm– 760 nm [73]; measured in $lm \cdot W^{-1}$) or when measuring the current generated by a solar cell (usually expressed in $A \cdot W^{-1}$[74]) (see Figure 2.2).

Photons with wavelength between 400 nm and 700 nm are the main drivers of photosynthesis. Therefore, this region of the electromagnetic spectrum is referred to as photosynthetically active radiation (PAR) [70, 75]. When only photons within the PAR region are considered, the radiation intensity can be expressed as photosynthetic photon flux density (PPFD, $\mu mol \cdot m^{-2} \cdot s^{-1}$). To calculate the total amount of PAR photons delivered during a day on a surface; the PPFD can be integrated over the duration of the light period (photoperiod, $h \cdot d^{-1}$), which results in the daily light integral (DLI, $mol \cdot m^{-2} \cdot d^{-1}$) [76, 77].

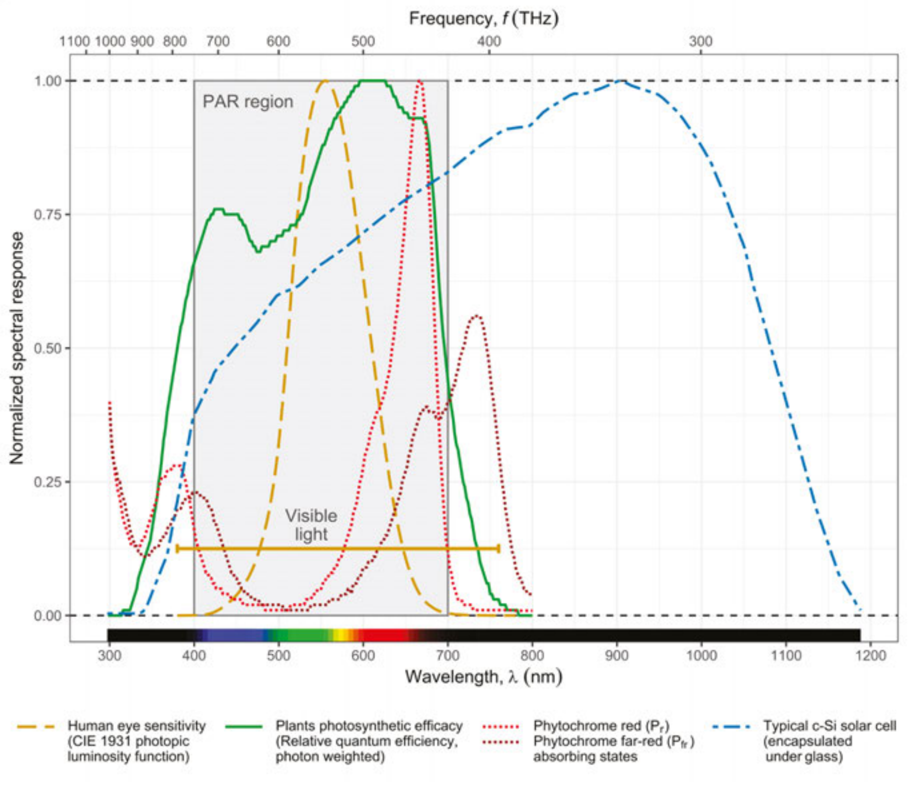



Figure 2.2: Comparison of the normalized spectral response to monochromatic radiation for: the human eye under well-lit conditions (CIE 1931 luminosity function for photopic vision, where the maximum at 540 THz corresponds to 683 $lm \cdot W^{-1}$ [78]); for the instantaneous photosynthetic efficacy of plants (photon-weighted relative quantum efficiency, with a peak of 0.07 – 0.08 µmol $CO_2$ fixed per µmol of absorbed photons of λ around 610 nm [70, 72, 79]); for phytochrome red ($P_r$) and far-red ($P_{fr}$) absorbing states [79, 80]; and for a typical crystalline silicon (c-Si) solar cell under glass (with peak spectral response between 0.6 – 0.7 $A \cdot W^{-1}$ [74]).

Research has shown that not all photons within the PAR region contribute equally to the process of photosynthesis; some wavelengths are absorbed more efficiently and there exist interactions and synergies between photons of different frequencies in comparison to applying only monochromatic light [36, 55, 71, 81]. Recent studies have gathered evidence that far-red photons (up to 750 nm) also support and impact photosynthetic activity [82, 83].

The amount of PAR in a location is not among the standard meteorological parameters measured by weather stations, and despite being easily available, quantum sensors are normally not installed. However, values of global horizontal irradiance ($G_h$) measured with a thermopile pyranometer can be used to estimate the PPFD considering the proportion of PAR to $SW_{280-3000\ nm}$ as well as the energy content of the PAR photons ($E_{PAR}$) (see Equation 3):

$$PPFD = G_{h,280-3000\ nm} \cdot \left(\frac{PAR_{400-700\ nm}}{SW_{280-3000\ nm}}\right)\left(\frac{1}{E_{PAR}}\right) \quad (3)$$

Since the energy of the photons depends on their wavelength, without actual spectral measurements, this approximation is bound to a certain degree of error. Numerous investigations have been made in order to improve the understanding on how the proportion of PAR in the solar spectrum changes throughout the day based on atmospheric conditions, within seasons and between location [84–91]. A recent study showed that using a fixed PAR:SW ratio of 0.45 and an average $E_{PAR}$ of 0.223 $J \cdot \mu mol^{-1}$ resulted in PPFD values deviating less than 5% from the actual measured amounts [56]. Equation 4 below applies these assumptions in Equation 3; implying that in average 45% of the solar radiation reaching the Earth's surface is within the PAR region, resulting in roughly 7.3 mol of PAR photons per kWh of $SW_{280-3000\ nm}$ [77]:

$$PPFD \approx G_{h,280-3000\ \mathrm{nm}} \cdot (0.45)(4.484\ \mu mol \cdot Ws^{-1}) \quad (4)$$

Besides providing energy, radiation serves as an information source to plants. They are able to detect a broader spectrum than human eyes and react to subtle changes in their surroundings, triggering sophisticated processes based on those light signals [71, 92, 93]. Specialized photosensor pigments control the photomorphogenesis, which is the development of plants in response to the spectrum of light [55]. The phytochrome which absorbs light in the red (R, 660 ± 20 nm) and far-red (FR, 730 ± 20 nm) regions [80, 94, 95] (see Figure 2.2); as well as the cryptochrome absorbing mainly UVA, blue (B, 455 ± 35 nm) and green light (G, 535 ± 35 nm) [96] are of special interest.

In general, the light quality or spectral composition greatly influences the morphology of plants [95, 97–100] which in turn impacts how much radiation they receive. Conversely, the light quantity affects mainly the photosynthesis rate and biomass production [101–103] but can alter their shape (Paper I).

## 2.2 Photoperiodic response of plants

The seasonal differences in the amount of sunlight and the duration of the photoperiod are the result of the rotation of the Earth and its orbital movement around the Sun. These variations become more noticeable as the latitude increases, and these changes are external and independent of local or global climate fluctuations [60] (see Figure 2.3).

Plants are able to detect even subtle differences in the natural photoperiod and adapt their development accordingly in a reaction known as photoperiodism [104–106]. Their light receptors are very sensitive and capable of detecting small amounts of radiation (PPFD < 1 $\mu mol \cdot m^{-2} \cdot s^{-1}$); perceiving even the faint light of twilight before sunrise and after sunset and use it as cues for the seasonal daylight duration [107].

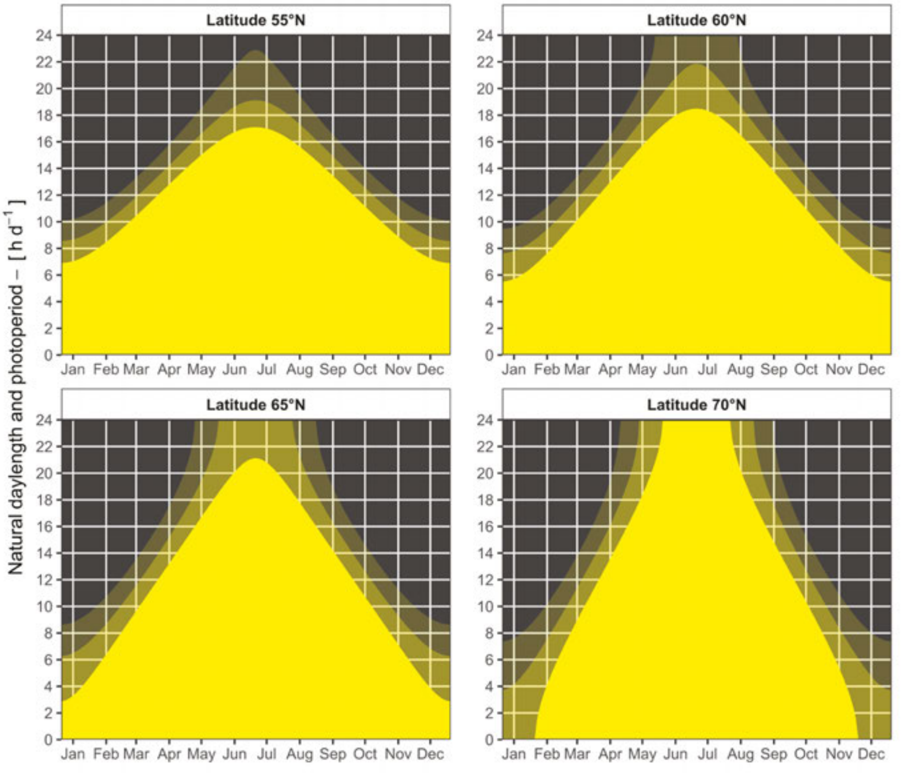



Figure 2.3: Natural daylength and photoperiod ($h \cdot d^{-1}$) during the year in four northern latitudes (55°, 60°, 65° and 70°). The solid yellow region represents the daytime defined as the period when the sun is above the horizon. The two increasing levels of transparency correspond to the civil (0° to 6° below the horizon) and the nautical twilight (6° to 12° below the horizon) respectively [108, 109] (see Paper IV).

In northern latitudes, the daylength usually starts decreasing weeks before the temperatures fall and the autumn frost nights with subzero temperatures begin [110] (see Figure 2.4). Plant species in these regions have adapted as a result and use the duration of daylight as a reliable indicator to start preparing for the winter once the photoperiod reaches a critical length [111].

Forest nurseries can use this evolutionary feature to their advantage by adjusting the light regimes and considering the critical photoperiod of their seedlings based on the provenance of the seeds [112]. Modern greenhouses allow implementing different strategies that manipulate the photoperiod. These include: prolonging the growing season by extending the daylength during the morning or evenings [113–115]; preventing the bud set by applying night interruption cycles [116, 117]; or promoting early growth cessation by creating shorter photoperiods and excluding the natural light inside the greenhouse using automatic blackout curtains [118–121].

In the novel year-round concept, the photoperiod can be easily controlled by switching the LED lamps; especially during the indoors pre-cultivation phase which occurs independent from outdoor conditions (Papers I, II, III).

## 2.3 Vegetation period and seedling cultivation

The climate in the boreal forest is characterized by short summers with moderately warm and moist days, contrasted by long and cold winters with very limited sunshine (see Figures 2.3) [122]. Together with the right amount of light, having the right temperature is crucial for plant development and the extreme fluctuations in this region considerably restrict the growing season.

The vegetation period is defined as the part of the year when the daily average ambient temperature ($T_a$) stays above a certain threshold at which plants can grow (usually defined at +5°C) [123]. For northern Europe, depending on the location, this period can last less than 200 days, starting halfway during spring and lasting only until early autumn [124] (see Figure 2.4). Forest species in the region have evolved to cope with the harsh conditions and adapted their growth cycles accordingly [125, 126]

Nurseries in these areas have also adjusted their cultivation regimes in order to follow the strong seasonal variations. The transition from bare-root seedlings towards containerized stock production and the implementation of greenhouses allowed the extension of the vegetation period [14]. However, even modern greenhouses reach a point when they cannot compensate the cold temperatures outdoors and the heating demand becomes too high, so cultivation is suspended during the coldest months of the year [27].

Nowadays, conventional production of containerized seedlings in forest nurseries of the Nordic countries consists of two or three batches per year using a combination of greenhouse and outdoor cultivation. The seeds are usually sown directly in the final container (volume between 25-120 $cm^3$) with the first batch starting in early spring [16, 127]. The germination and initial growth phase take place for a couple of months inside a greenhouse, which can contain up to 2 million seedlings per greenhouse at densities ranging between 300-1600 plants per $m^2$ [5, 15, 17].

Once the weather conditions are favorable, the seedlings of the first batch are transferred outdoors for further cultivation at the nursery. The second batch continues to grow inside and is transferred outside in the middle of the summer. Given that the third batch is sown so late in the season, it might remain in the greenhouse even during August [128].

In autumn, some of the spring-sown seedling from the first batch might be transported and planted at the regeneration sites [129]. However, more often the seedlings are prepared for cold storage by promoting early growth cessation and inducing bud. This is achieved by reducing the photoperiod in a process known as short-day (SD) treatments [118–121]. Together with shorter photoperiods, temperature is a crucial factor affecting the degree of cold hardiness in conifer seedlings [130–133].

When the seedlings are dormant and are able to tolerate freezing temperatures, they are stored either in cardboard boxes and taken into refrigerated warehouses with climate control or are left outdoors and protected under cover of snow [134–137]. The seedlings remain stored until the following year when they are either transported for planting in the forest [138, 139]; or are further grown for another season at the nursery and afterwards taken for planting on the second autumn after sowing [127].

As an alternative to the current nursery practices, a novel concept for year-round cultivation of forest seedlings has been under development during the past decade [31, 46, 49, 116, 140, 141]. This new approach consists of an indoor pre-cultivation phase under LED lamps using smaller container volumes (around 3.5-13 $cm^3$) at higher cultivation densities (about 1800-3500 seedlings per $m^2$) [18, 20, 28], followed by transplanting to a larger container for an outdoor growth phase (Paper I). This opens future possibilities for large-scale production of high-quality seedlings by extending the cultivation time through the winter. It reduces the area needed and increase the speed at which the plants are available for reforestation and afforestation purposes [18, 30].

However, one of the main challenges is that before cold storage, treatments to induce cold hardiness must be applied on very young seedlings (about five weeks old) which might not have enough carbohydrate reserves [137, 142–144]. This in contrast with the conventional methods where the cold hardiness treatments start after 15 weeks or more of growth [14, 145]. Currently, there have been only a few studies attempting to induce cold hardiness in very young conifer seedlings [18, 146] and even fewer have been carried out using only artificial lights in growth room facilities [141].

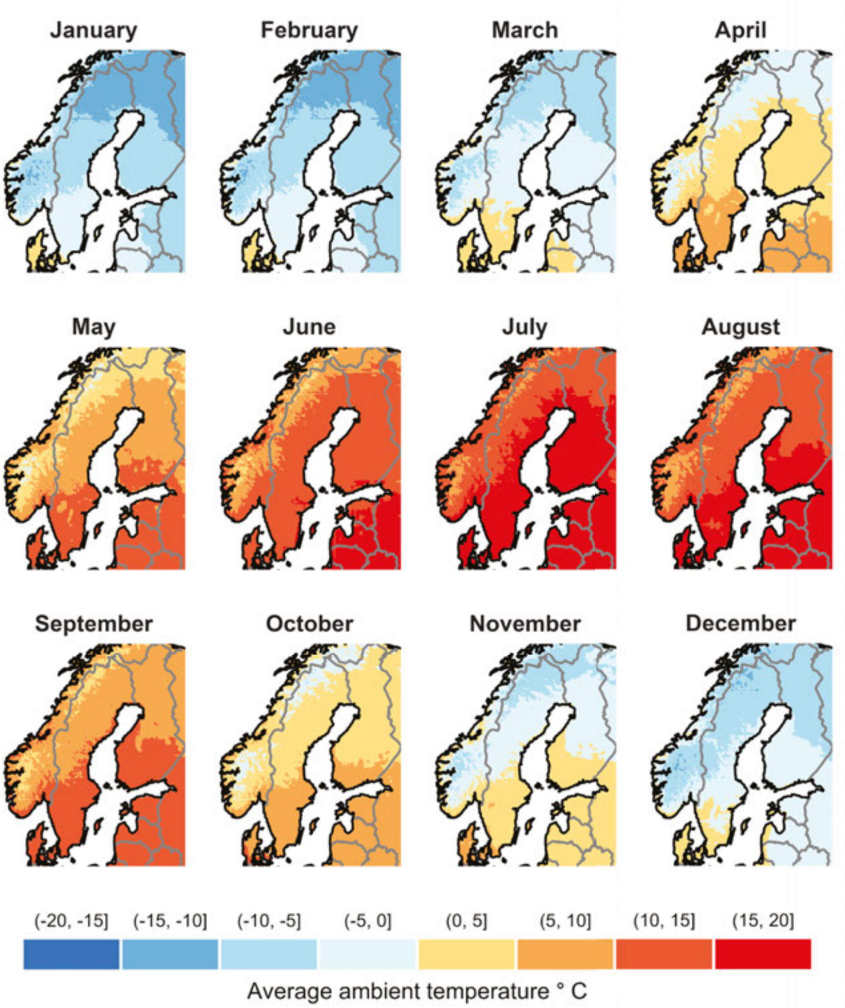



Figure 2.4: Monthly average daily ambient temperature ($T_a$, °C) maps for the Nordic and Baltic countries. Values from the ECMWF-ERA-5 dataset (coverage from 2005 – 2016) retrieved from PVGIS [147] in a 0.1° × 0.1° grid extending from 54.5° N to 70° N in latitude and 4.5° E to 31.5° E in longitude. (see Paper IV).

For a successful introduction of the novel concept, new treatments for induction of cold hardiness need to be developed. This will allow seedlings cultivated indoors during the winter months to be cold stored before transplanting them to outdoor conditions during the vegetation period for further growth (Paper II).

## 2.4 Greenhouse supplementary lighting

Plant growth is affected by a wide range of environmental parameters including light, temperature, moisture, availability of nutrients and $CO_2$ concentration [148]. The principle of limiting factors dictates that the rate of photosynthesis will be restricted by the lowest of these variables [81, 149]. This means that even if improvements in greenhouse thermal control are able to solve the temperature limitations; the low amounts of natural light during the winter months would further restrict the cultivation of seedlings [26].

Forest nurseries above 40° latitude routinely use artificial lighting at some point to compensate for the low natural radiation levels outdoors during spring and autumn [25]. Although relying entirely on conventional lighting sources would result in excessive electricity and lamp replacement costs [35]; it is possible to use artificial lights to build upon the available sunlight [150].

In a greenhouse, the amount of supplementary light required is one of the most complicated factors to plan and control with precision [151]. The quantity of natural light reaching at the cultivation level greatly depends on several factors such as: the age and type of glazing material, the greenhouse design and structural components as well as the accumulation of dust or snow. All of these parameters influence how much of the radiation outdoors is attenuated before reaching the plants and ultimately how much supplementary lighting will be necessary to reach a desired PPFD level [53, 151–153].

The global or hemispherical PAR transmittance coefficient $\tau_{h, PAR}$, %) considers the PPFD inside the greenhouse in comparison to total PPFD outdoors. This value can range between 35% and 70% depending on the individual conditions [24, 154–158]. Nevertheless, $\tau_{h, PAR}$ can be used as a starting point to estimate the levels inside the greenhouse based on outdoor measurements, approximations using Equation 4 or working with monthly average DLI maps (e.g., in [77, 159, 160] or Figure 2.7). Once the natural light indoors is known, the supplementary lighting requirements can be estimated.

There are several types of grow lamps that can be used in a greenhouse [25] (see Figure 2.5). If the objective is to extend the photoperiod, low intensity fluorescent lamps can suffice. However, if the goal is to provide the bulk of photosynthetic light, high-intensity discharge (HID) lamps like high-pressure sodium (HPS) or metal-halide (MH) lamps are normally required [43, 161].

Among the main disadvantages of fluorescent and HID lamps are their radiative heat emissions, difficulties to control and increased wear when cycled too often [35, 43]. In contrast, modern LED lamps have long lifespans, can be cycled many times over short intervals and are easily dimmed [162].

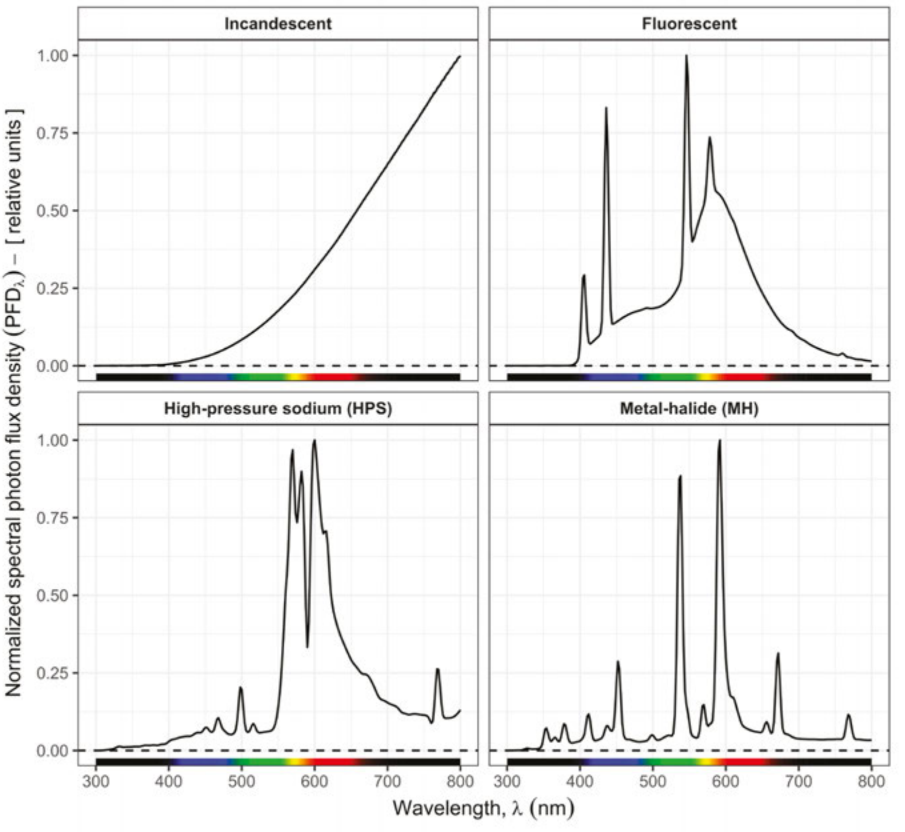



Figure 2.5: Normalized spectral photon flux for conventional luminaires used in greenhouse cultivation [25]: incandescent lamp (top left; considered the first generation of growth lamps [163]); fluorescent lamp (top right); and high discharge lamps (HID) including high-pressure sodium (HPS) and metal-halide (MH) lamps (bottom row) (OSRAM Licht AG; Munich, Germany; open data available in [164]).

LEDs are semiconductor photonic devices that convert electrical energy into optical radiation though the process of electroluminescence [165]. The light output can be controlled either by adjusting the amount of current that flows through them (amplitude modulation, AM) or by supplying the current at very short intervals (pulse width modulation, PWM) [166]. Both dimming methods have shown no negative effect on plant photosynthesis unless the PWM intervals are relatively long ( >20 ms) [167, 168]. Thus, the electrical power input and light output can be considered linear within a usable range.

Due to their longer lifetimes and adaptive control possibilities, LED lamps have become a realistic alternative for plant cultivation; allowing nursery managers to save energy by providing only the right amount of light to the seedlings at the time when it is needed [162, 168–170] (Paper I, IV).

## 2.5 Sole-source lighting for indoor cultivation

In some circumstances, closed plant production systems with sole-source LED lighting can be used instead of greenhouses [39, 171]. Growth rooms with multi-level cultivation allow a maximum yield and benefit from a standardized and controlled environment independent from outdoor conditions [172].

On the other hand, the evident disadvantage of excluding sunlight results in high electricity demand for artificial lights and climate control [172, 173]. Recent studies suggest that between 70% and 80% of this consumption is due to lighting while the rest is mainly cooling and dehumidification [174, 175].

For a closed growth room with a constant light intensity, the DLI provided by the lamps can be calculated using the PPFD setting and the duration of the photoperiod (adjusting the units) in Equation 5 (also used for Figure 2.6):

$$DLI_{lamps} = PPFD_{lamps} \cdot photoperiod \cdot \left(0.0036 \frac{mol \cdot s}{\mu mol \cdot h}\right) \tag{5}$$

Although the efficiency of lamps is usually reported as a ratio of the luminous power output to the electrical power input; for plant cultivation, it is more useful to compare their efficacy. This is a measure of the total photon output rate (in $\mu mol \cdot s^{-1}$) against the electrical power input (in W). When only the PAR photons are considered, this parameter is known as photosynthetic photon efficacy  PPE, $\mu mol \cdot J^{-1}$) [35, 162].

If the efficacy is measured using a flat-plane integration method and assuming an even distribution where most light reaches the canopy [35]; the PPE  $\mu mol \cdot J^{-1}$) can be used to estimate the daily electricity consumption for lighting ($E_{el,\ lamps}$, $Wh \cdot m^{-2} \cdot d^{-1}$) per cultivation surface, using Equation 6:

$$E_{el,lamps} = \frac{PPFD_{lamps} \cdot photoperiod}{PPE} \tag{6}$$

In the past years the efficacy of growth lamps, especially for LEDs, has improved significantly. A study made in 2014 comparing the best-in-class HID and LED lamps concluded that both had similar efficacies of around 1.70 $\mu mol \cdot J^{-1}$ [35, 176]. While the HID lamps had reached 2.10 $\mu mol \cdot J^{-1}$ by 2018 [177, 178]; the LED manufactures achieved top efficacies between 2.5 and 2.8 $\mu mol \cdot J^{-1}$ per fixture in 2020 and even higher values are expected, between 3.4 and 4.1 $\mu mol \cdot J^{-1}$, during this decade [162].

The rapid improvement in their efficacy together with the dimmability and cycle control capabilities are unique features of LEDs. These could enable a year-round cultivation concept with indoor sole-source periods as well as seasonal combinations of sunlight and LED lamps [162] (Paper IV).

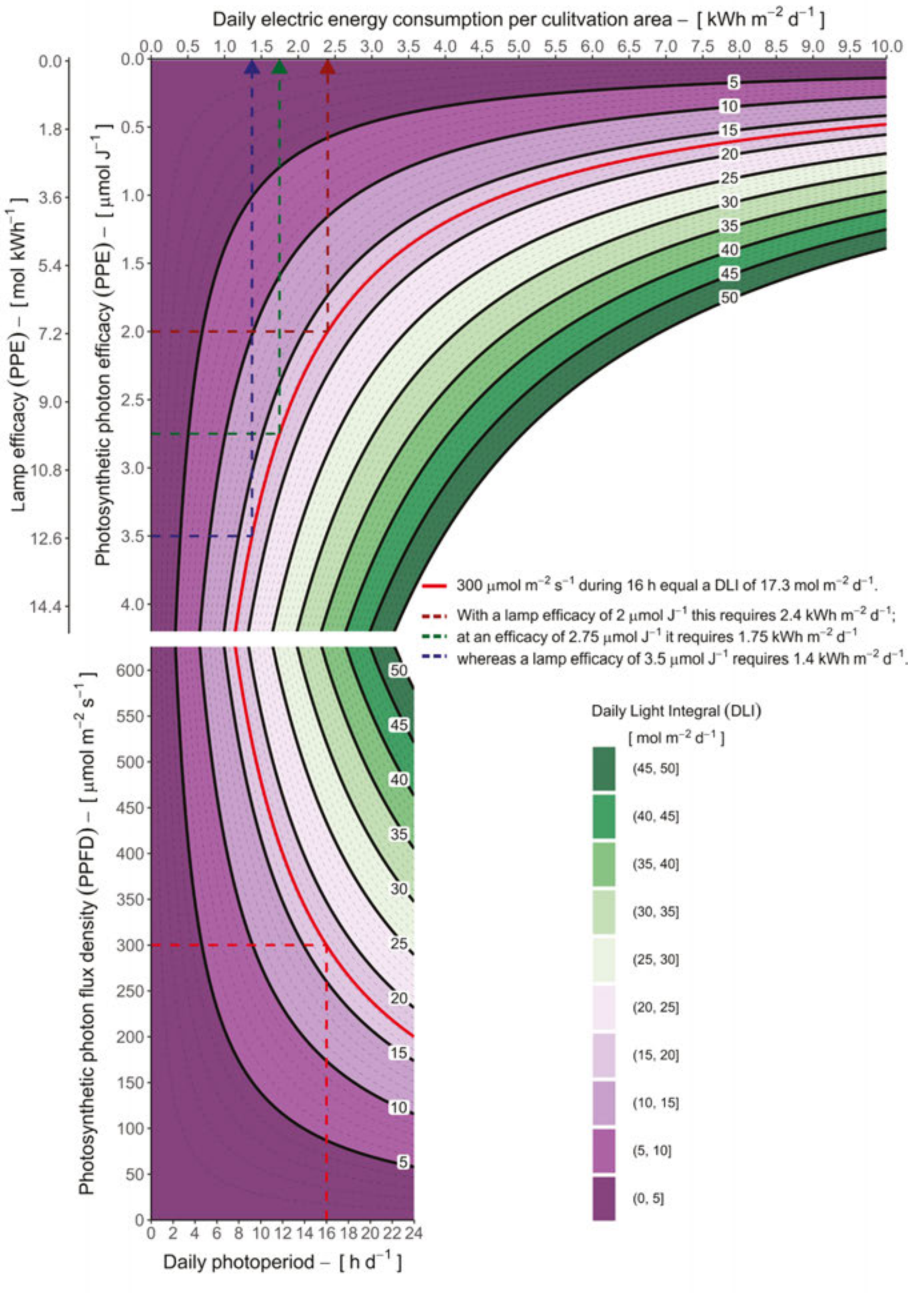



Figure 2.6: Daily PAR output of sole-source lighting ($DLI_{lamps}$, mol·m$^{-2}$·d$^{-1}$) and the corresponding electric energy requirements per cultivation area ($E_{el}$, kWh·m$^{-2}$·d$^{-1}$) based on the PPFD (µmol·m$^{-2}$·s$^{-1}$), the photoperiod (h·d$^{-1}$), and the lamp's efficacy (PPE, µmol·J$^{-1}$) also in equivalent units typically found commercially (mol·kWh-1). The red dashed lines are an example for typical growth-room cultivation settings while the contiguous red line is the resulting $DLI_{lamps}$. (Paper IV)

## 2.6 Light shock stress upon outdoor transplanting

In contrast to the low PPFD levels of the winter months (see Figure 2.7), the abundant levels of solar radiation during the summer introduce a potential risk for light shock stress, especially upon transplanting young indoor-grown seedlings to outdoor conditions [179–181]. The transplant stress can be further increased by additional abiotic factors such as high temperatures, lack of nutrients and drought [182, 183].

Although plants have developed a wide range of protection mechanism to avoid and recover from light-induced injuries [184, 185]; many of these regulating functions are not fully developed in young plants. This makes juvenile seedlings less efficient when utilizing the absorbed photons and more susceptible to photodamage, even in conditions that would normally not harm a mature plant [186, 187]. In an early cultivation phase, seedlings only have a few needles to rely on for photosynthesis. If these are not able to adapt fast to the new conditions after transplanting, they risk suffering from photoinhibition, which consists of a reduced photosynthetic efficacy and a slower $CO_2$ uptake that could negatively affect their growth [188].

Some of the seedlings' morphological attributes such as needle size, shape or stomatal density develop according to the light environment and are practically permanent, so new structures need to be formed when the conditions change [189–193]. In contrast to needles that grew under high light intensities ('sun' needles), needles that grew under low light intensities ('shade' needles) are devised to absorb as much PAR as possible [194]. If those 'shade' needles are exposed to direct sunlight, the intense irradiance could scorch them and reduce their chlorophyll levels [195].

Most studies regarding cultivation under LEDs have focused mainly on optimizing the indoor growth conditions [47–51]. However, both the light quality and intensity inside LED growth rooms differ considerably from the natural outdoor conditions. As a consequence, seedlings pre-cultivated in these facilities may possibly lack the protective mechanisms against high UV photon flux density (UV PFD) levels, since this is almost absent in the light sources used during the indoor cultivation phase.

Evidence of a stress upon transplanting could indicate that seedlings need to develop and accumulate the necessary UV absorbing pigments already during pre-cultivation [196, 197] and may as well require an adaptation phase under shade cloths when transferred to outdoor conditions [198–200].

Therefore, before adopting a new technology that allows production of forest seedlings on a year-round basis in the boreal region, light shock stress has to be further investigated and cultivation protocols that allow its mitigation need to be established. (Paper III).

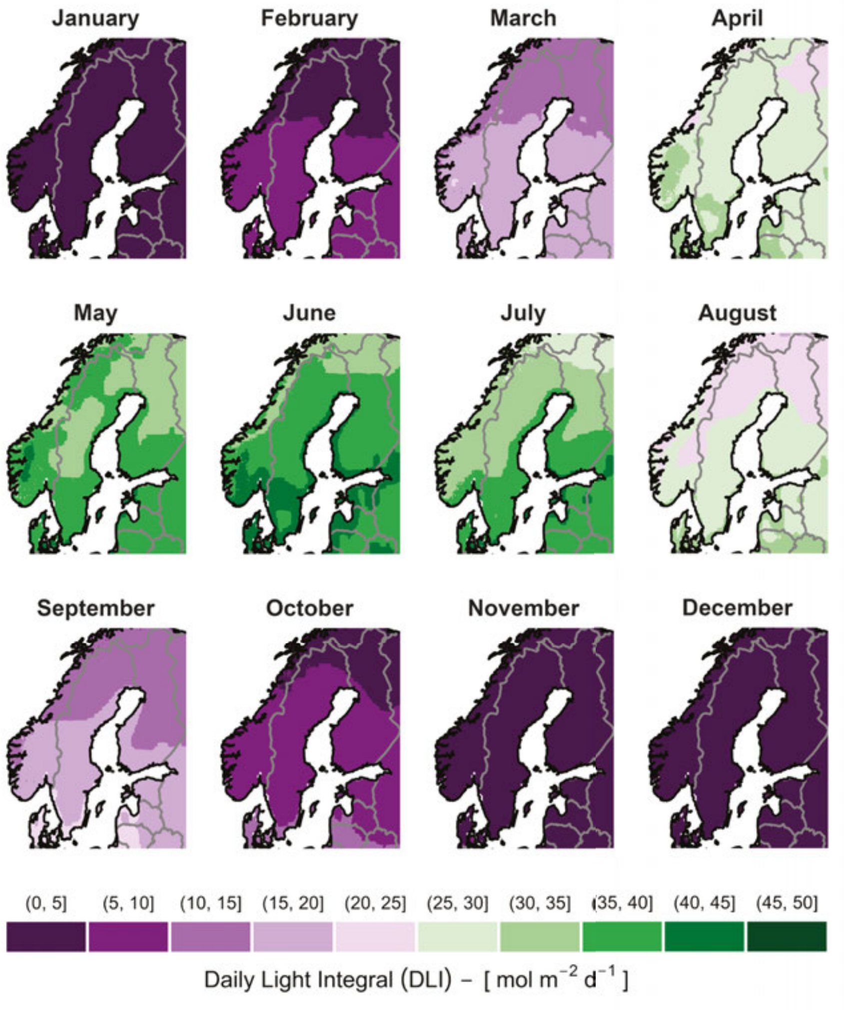



Figure 2.7: Monthly average photosynthetic daily light integral (DLI, mol·m$^{-2}$·d$^{-1}$) maps for the Nordic and Baltic countries. Values from the ECMWF-ERA-5 dataset (coverage 2005 – 2016) retrieved from PVGIS [147] in a 0.1° × 0.1° grid extending from 54.5° N to 70° N in latitude and 4.5° E to 31.5° E in longitude (calculated using average hourly $G_h$ values in Equation 4 over a 24 h period; see Paper IV).

## 2.7 Greenhouse integrated PV and agrivoltaics

While one of the main obstacles for deploying artificial lighting in plant growth is the electricity consumption [172], solar photovoltaics (PV) offers a possibility to offset some of this energy [201]. Even though photosynthesis and PV essentially compete for radiation, recently there has been an increased interest in agrivoltaics (APV) as a way to co-develop agriculture and PV in the same space [202, 203]. Together with the installation of PV modules in agricultural fields [204–206]; greenhouse integrated photovoltaics (GHIPV) as a form of APV has been also successfully implemented [207–210].

Among of the main advantages of GHIPV is that no extra land surface is used and instead uses existing or planned structures [211]. During the summer when the solar irradiance is abundant, the PV modules can absorb some of that energy, providing shelter and reducing the need for shading screens to protect the plants [200, 212]. Moreover, the spectral response of some PV technologies does not overlap entirely with that of PAR absorption (see Figure 2.2), allowing the installation of semitransparent solar cells [213–215].

The nominal power of a PV installation ($P_{PV, STC}$, W) describes the electric power output of the system when measured at standard test conditions (STC) [216]. The efficiency at STC $\eta_{STC}$) relates the $P_{PV, STC}$ over the test input irradiance ($G_{STC}$ = 1000 W·m$^{-2}$) on the PV area ($A_{PV}$, m$^2$). Depending on their technology, PV modules commercially available have $\eta_{STC}$ ranging between 12%-22% [217]. Even though different materials have differences in their spectral responsivity and thermal behaviors, in practice the spectral mismatch accounts for less than 5% energy yield differences [74, 218, 219]. For this reason, for initial estimations, it is usually assume that systems with equal $P_{PV, STC}$ will have a similar yearly energy output regardless of the technology if all other parameters are equal [220, 221].

The PV coverage ratio ($PV_R$) is the fraction of the available surface on the roof (or land) covered by the PV [222]. One of the main differences between traditional building applied photovoltaics (BAPV, the solar modules are superimposed onto the building) as well as building integrated photovoltaics (BIPV, the modules are part of the building envelope), compared to GHIPV and APV where plants are involved; is the need for optimizing the $PV_R$ since this will have a significant effect on shading and photosynthesis [202].

Determining the $PV_R$ for a GHIPV or APV field requires an optimization that balances the electricity output with the light requirements of the species [158, 204, 223–230]. In southern Europe, GHIPV with a $PV_R$ between 10% and 20% presented only minor reduction in the crop yields, even for shade-intolerant plants like tomatoes [205, 211, 223]. Additional studies for Northern Europe are needed to determine the ideal $PV_R$ for different species.

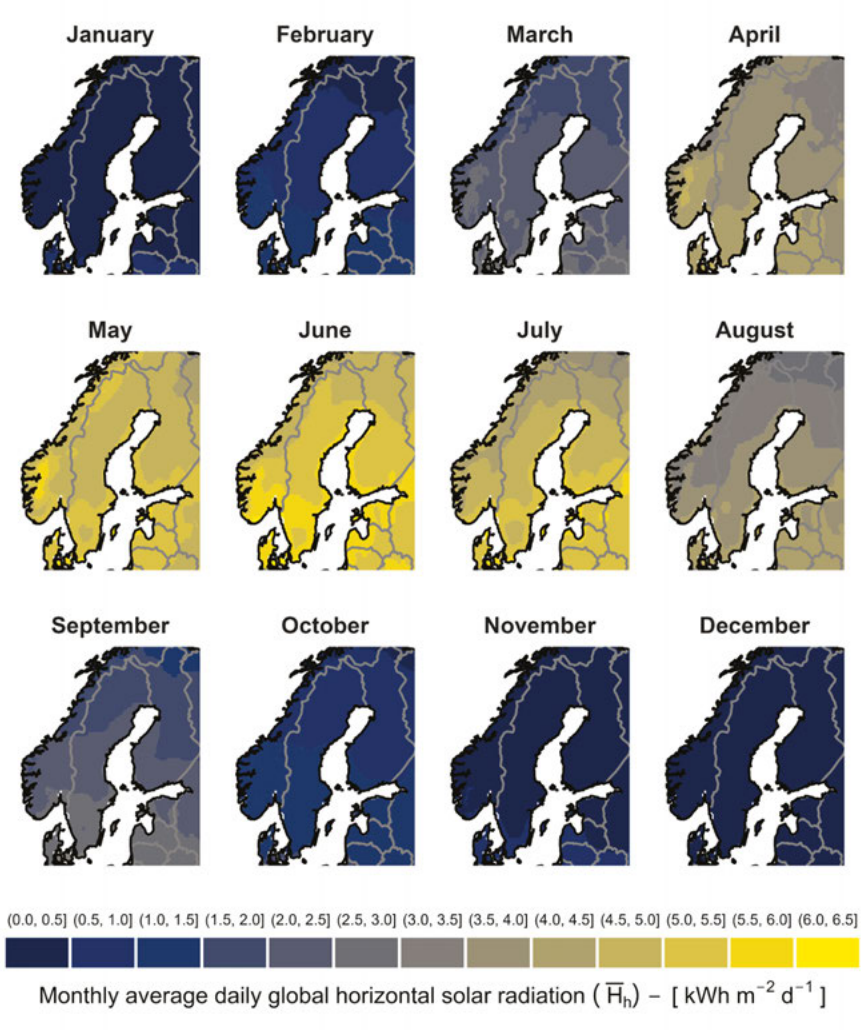



Figure 2.8: Monthly average daily global horizontal solar radiation ($\overline{H}_h$, kWh·m$^{-2}$·d$^{-1}$) maps for the Nordic and Baltic countries. Values from the ECMWF-ERA-5 dataset (coverage 2005 – 2016) retrieved from PVGIS [147] in a 0.1° × 0.1° grid extending from 54.5° N to 70° N in latitude and 4.5° E to 31.5° E in longitude. (see Paper IV).

Once the $PV_R$ has been optimized, the maximum recommended $P_{PV,\,STC}$ for a specific roof area can be estimated as a function of $\eta_{STC}$ of the photovoltaic modules selected and the roof area available, using Equation 7:

$$P_{PV,\,STC} \leq \left(PV_R \cdot A_{roof}\right)\left(G_{STC} \cdot \eta_{STC}\right) \tag{7}$$

With $P_{PV,\,STC}$ decided, solar resource maps (e.g., in [231–233] or Figure 2.8) can be used to find regions with higher potential by approximating the energy yield, accounting for roof orientation and other system losses [220] (PaperIV).

# 3 Materials and methods

*A more detailed description of the materials and methods used at each stage can be found in the corresponding appended Papers I-IV.*

## 3.1 Plant material

The seeds used in all of the studies had the following characteristics:

- Norway spruce (*Picea abies* (L.) Karst)
  The seeds had a provenance of Vitebsk, Belarus (lat. 55.2°; long. 30.2°) with a germination energy of 96.5% quantified after 7 days and a germination rate of 99.0% measured after 21 days.

- Scots pine (*Pinus sylvestris* L.)
  The seeds came from an orchard in Gotthardsberg, Sweden (lat. 58.4°; long. 16.6°) with both germination energy (after 7 days) and germination rate (after 21 days) of 99.8%.

The germination energy describes the vigour of the seeds and the simultaneity of sprouting under optimal conditions, whereas the germination rate is a measure for the viability of the seeds and their ability to form normal plants within a typical period for the species [234].

### 3.1.1 Sowings

The seeds were sown directly into mini-plug trays (QP D 576 QuickPot®, Herkuplast-Kubern; Ering, Germany) of high container density (tray size: 310 × 530 mm; density: 3500 seedlings per $m^2$; 576 cells per tray; volume per cell: 3.5 $cm^3$). In order to facilitate transplanting, the mini-plugs were filled with a stabilized peat containing a binding agent (Preforma PP01, Jiffy International AS; Kristiansand, Norway).

For each of the studies, the following independent sowings were done:

Light quality during indoor pre-cultivation (Paper I):

- Three separate sowings (7th March, 15th May and 13th August 2013) with 8 trays of mini-plug containers per species were sown; randomly assigning two trays per light quality treatment (all at 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$): Fluorescent, LED 1, LED 2, LED 3 (Table 3.1).
- The seedlings used in the forest field trial were taken from the second sowing (15th March 2013).

Light intensity during indoor pre-cultivation (Paper I):

- Three separate sowings (20th January, 26th February and 13th April 2015) with two trays of mini-plug containers for each light intensity treatment (50, 100, 200, or 400 $\mu mol \cdot m^{-2} \cdot s^{-1}$) and species were sown (total 8 trays per sowing per species).

Short-day treatments for cold hardiness induction (Paper II):

- Two separate sowings (9th February and 19th March 2015) with six trays per species were sown. After the pre-cultivation phase, two trays per species were randomly assigned to one of the temperature treatments (5°C, 10°C or 20°C; each in a separate growth room).

Light shock mitigation (Paper III):

- Three separate sowings (5th May 2014, 17th June 2014 and 25th May 2015) with four trays of mini-plug containers per species were sown. After the pre-cultivation phase, one trays per species was randomly assigned to one of the different indoor treatments (Control, High intensity, UVA 30 or 60 min, UVA 240 min).

## 3.2 Light sources

The same set of luminaires was used for all the trials here presented. Since LED lamps used were prototypes, two lamps of each model were measured to create an average spectral and electrical profile of each. These characteristics are fully reported in in Table 3.1 using a similar format as suggested in literature [235] to facilitate comparability and repeatability of the results.

The LED grow lamps used in the studies have a spectrum that was specifically tailored for plant growth (B100, Valoya OY; Helsinki, Finland). As a control, conventional fluorescent grow lamps (Fluora; OSRAM Licht AG; Munich, Germany) were used when comparing the light quality (Paper I). During the light shock mitigation treatments, UVA-LED lamps (B100, Valoya OY; Helsinki, Finland) were also used (Paper III).

### 3.2.1 Spectral measurements

The luminaires were placed 25 cm directly above the quantum sensor of a JAZ spectroradiometer (JAZA3088, Ocean Optics, USA) in order to measure the $PFD_\lambda$ for the range between 300-900 nm. This was done in a windowless and dark room with black clothes covering all surfaces to reduce reflection. The averaged spectral curve was normalized against the highest $PFD_\lambda$ registered for each measurement [236] and the PFD values were aggregated in waveband intervals of 100 nm. The corresponding yield photon flux (YPF) density was calculated by pointwise multiplication with the relative quantum efficiency (RQE) curve of photosynthesis [75, 79] (see Figure 2.2).

Spectral ratios were calculated to estimate possible photomorphogenic responses. The effect of light on the cryptochrome was measured using the blue to green ratio (B/G) ratio, with B centred at 455 ± 35 nm and G centred at 535 ± 35 nm. This photoreceptor is known for regulating the circadian clock and affecting the hypocotyl length in adaptation to blue and UV light [96].

The possible effects on the phytochrome are particularly important since this pigment is known for affecting processes such as germination, stem elongation and stomatal opening, which can have applications in seedling cultivation [45, 113, 114, 117, 237]. The red to far-red (R/FR) ratio was calculated with R centred at 660 ± 20 nm and FR at 730 ± 20 nm [235].

The phytochrome can exist in two interconvertible forms: as a red light absorbing form ($P_r$) that is considered biologically inactive, and a far-red light absorbing form ($P_{fr}$) that triggers the photomorphogenic responses [80, 94, 95]. The relative concentration of $P_r$ under a constant spectrum can be estimated using the phytochrome photostationary state (PSS, Equation 8); where $\sigma_\lambda$ is the action spectra and PSS is bounded between 0.1-0.89 due to the spectral overlap of both forms [79] (see Figure 2.2):

$$PSS = \frac{P_r}{P_r + P_{fr}} = \frac{\sum_{300}^{800} \mathrm{PFD}_\lambda \cdot \sigma_{r,\lambda}}{\sum_{300}^{800} \mathrm{PFD}_\lambda \cdot \sigma_{r,\lambda} + \sum_{300}^{800} \mathrm{PFD}_\lambda \cdot \sigma_{fr,\lambda}} \tag{8}$$

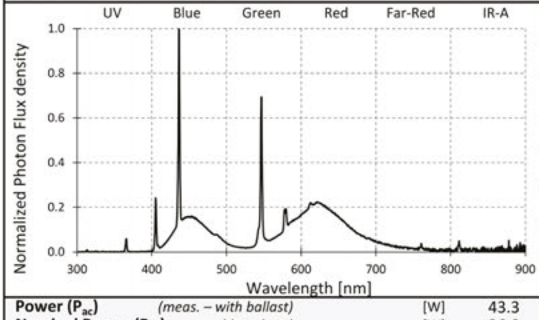
### 3.2.2 Electrical measurements

The LED lamps consisted of two components: a power supply unit (PSU) and the luminaire itself. The PSU includes an AC/DC converter that has an input of 110-277 Vac and a maximum current draw of 2 A. The luminaire then receives between 135-425 Vdc and a direct current of 0.034-0.345 A. The light output of the LED lamps was regulated using an AM dimmer that varied the current flow through the LEDs and thus photon output.

The current was measured using a Fluke 45 True RMS multi-meter (Fluke Corporation; Everett, WA, USA) while the voltage using an EX520 industrial multi-meter (Extech Instruments Corporation; Nashua, NH, USA).

Table 3.1: Characteristics of the different light spectra used in the studies.

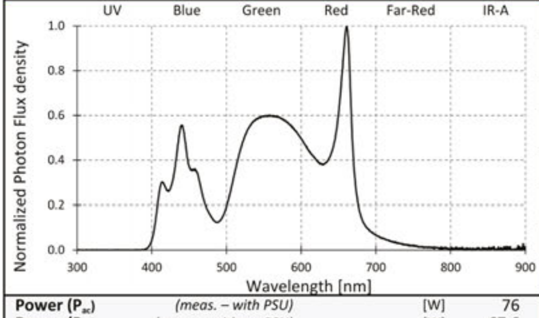
**Fluorescent**




| | | | |
|---|---|---|---|
| Power ($P_{ac}$) | (meas. – with ballast) | [W] | 43.3 |
| Nominal Power ($P_{ac}$) | (datasheet) | [W] | 36.0 |
| Voltage (V) | (measured) | [V] | 233.1 |
| Current (I) | (measured) | [A] | 0.205 |
| PPE | (from point measurement 25 cm below the lamp) | [$\mu mol \cdot m^{-2} \cdot J^{-1}$] | 0.9 |
| | | [$mol \cdot m^{-2} \cdot kWh^{-1}$] | 3.1 |

| Waveband | Photon flux density (PFD) [$\mu mol \cdot m^{-2} \cdot s^{-1}$] | % |
|---|---|---|
| Ultraviolet 300-399 nm | 0.3 | 0.1% |
| Blue 400-499 nm | 12.6 | 30.8% |
| Green 500-599 nm | 9.2 | 22.3% |
| Red 600-699 nm | 15.7 | 38.5% |
| Far-Red 700-799 nm | 2.1 | 5.1% |
| Near Infrared 800-900 nm | 0.8 | 1.9% |
| Total 300-900 nm | 41.0 | 100.0% |
| PAR 400-700 nm | 37.8 | 92.2% |
| YPF (photon-weighted) 300-800 nm | 33.0 | |
| PSS | (300-800 nm) | 0.82 |
| B/G | 420:490 nm / 500:570 nm) | 2.3 |
| R/FR | 640:680 nm / 710:750 nm) | 5.3 |
| Illuminance | [lx] | 3582 |

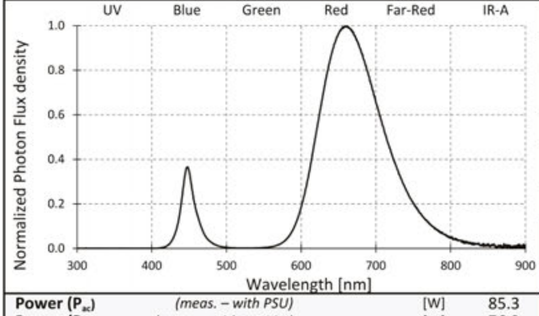
**LED 1**




| | | | |
|---|---|---|---|
| Power ($P_{ac}$) | (meas. – with PSU) | [W] | 76 |
| Power ($P_{dc}$) | (meas. – without PSU) | [W] | 67.6 |
| Voltage (V) | (measured) | [V] | 234.6 |
| Current (I) | (measured) | [A] | 0.3 |
| PPE | (from point measurement 25 cm below the lamp) | [$\mu mol \cdot m^{-2} \cdot J^{-1}$] | 2.6 |
| | | [$mol \cdot m^{-2} \cdot kWh^{-1}$] | 9.5 |

| Waveband | Photon flux density (PFD) [$\mu mol \cdot m^{-2} \cdot s^{-1}$] | % |
|---|---|---|
| Ultraviolet 300-399 nm | 0.2 | 0.1% |
| Blue 400-499 nm | 43.6 | 21.3% |
| Green 500-599 nm | 91.5 | 44.7% |
| Red 600-699 nm | 64.1 | 31.4% |
| Far-Red 700-799 nm | 3.5 | 1.7% |
| Near Infrared 800-900 nm | 0.4 | 0.2% |
| Total 300-900 nm | 204.6 | 100.0% |
| PAR 400-700 nm | 200.4 | 98.0% |
| YPF (photon-weighted) 300-800 nm | 173.9 | |
| PSS | (300-800 nm) | 0.85 |
| B/G | 420:490 nm / 500:570 nm) | 0.6 |
| R/FR | 640:680 nm / 710:750 nm) | 18.1 |
| Illuminance | [lx] | 13790 |

**LED 2**

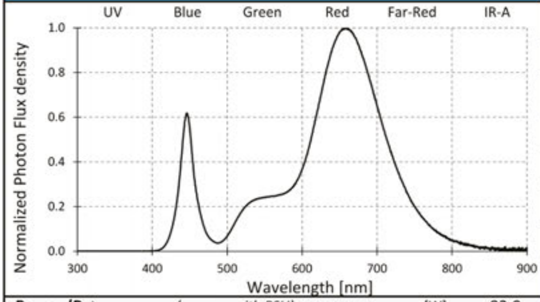



| | | | |
|---|---|---|---|
| Power ($P_{ac}$) | (meas. – with PSU) | [W] | 85.3 |
| Power ($P_{dc}$) | (meas. – without PSU) | [W] | 76.3 |
| Voltage (V) | (measured) | [V] | 232.6 |
| Current (I) | (measured) | [A] | 0.376 |
| PPE | (from point measurement 25 cm below the lamp) | [$\mu mol \cdot m^{-2} \cdot J^{-1}$] | 2.4 |
| | | [$mol \cdot m^{-2} \cdot kWh^{-1}$] | 8.5 |

| Waveband | Photon flux density (PFD) [$\mu mol \cdot m^{-2} \cdot s^{-1}$] | % |
|---|---|---|
| Ultraviolet 300-399 nm | 0.0 | 0.0% |
| Blue 400-499 nm | 20.0 | 7.7% |
| Green 500-599 nm | 4.6 | 1.8% |
| Red 600-699 nm | 175.3 | 67.3% |
| Far-Red 700-799 nm | 55.6 | 21.3% |
| Near Infrared 800-900 nm | 2.6 | 1.0% |
| Total 300-900 nm | 260.4 | 100.0% |
| PAR 400-700 nm | 202.1 | 77.6% |
| YPF (photon-weighted) 300-800 nm | 186.3 | |
| PSS | (300-800 nm) | 0.79 |
| B/G | 420:490 nm / 500:570 nm) | 28.1 |
| R/FR | 640:680 nm / 710:750 nm) | 3 |
| Illuminance | [lx] | 3609 |

Table 3.1 (continued form previous page)

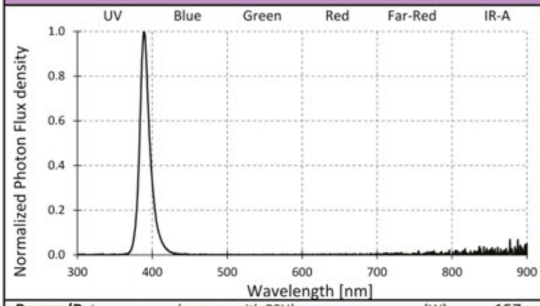
## LED 3




| | | | |
|---|---|---|---|
| Power ($P_{ac}$) | *(meas. – with PSU)* | [W] | 82.9 |
| Power ($P_{dc}$) | *(meas. – without PSU)* | [W] | 74.2 |
| Voltage (V) | *(measured)* | [V] | 234.6 |
| Current (I) | *(measured)* | [A] | 0.363 |
| PPE | *(from point measurement* | [$\mu mol \cdot m^{-2} \cdot J^{-1}$] | 2.4 |
| | *25 cm below the lamp)* | [$mol \cdot m^{-2} \cdot kWh^{-1}$] | 8.7 |

| Waveband | Photon flux density (PFD) [$\mu mol \cdot m^{-2} \cdot s^{-1}$] | % |
|---|---|---|
| Ultraviolet 300-399 nm | 0.0 | *0.0%* |
| Blue 400-499 nm | 27.5 | *11.4%* |
| Green 500-599 nm | 38.2 | *15.8%* |
| Red 600-699 nm | 133.4 | *55.1%* |
| Far-Red 700-799 nm | 39.3 | *16.2%* |
| Near Infrared 800-900 nm | 1.7 | *0.7%* |
| Total 300-900 nm | 242.0 | *100.0%* |
| PAR 400-700 nm | 201.0 | *83.1%* |
| YPF (photon-weighted) 300-800 nm | 181.8 | |
| PSS | (300-800 nm) | 0.79 |
| B/G | 420:490 nm / 500:570 nm) | 1.1 |
| R/FR | 640:680 nm / 710:750 nm) | 3 |
| Illuminance | [lx] | 7588 |

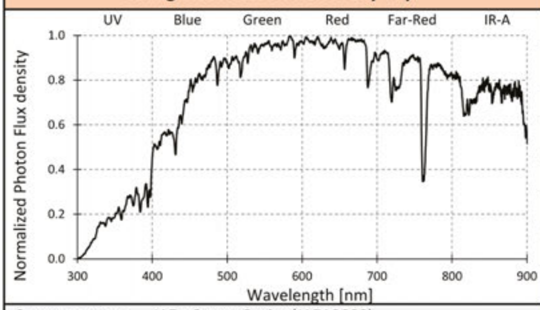
## UVA - LED




| | | | |
|---|---|---|---|
| Power ($P_{ac}$) | *(meas. – with PSU)* | [W] | 157 |
| Power ($P_{dc}$) | *(meas. – without PSU)* | [W] | 144.6 |
| Voltage (V) | *(measured)* | [V] | 234.4 |
| Current (I) | *(measured)* | [A] | 0.7 |
| PPE | *(from point measurement* | [$\mu mol \cdot m^{-2} \cdot J^{-1}$] | 0.1 |
| | *25 cm below the lamp)* | [$mol \cdot m^{-2} \cdot kWh^{-1}$] | 0.3 |

| Waveband | Photon flux density (PFD) [$\mu mol \cdot m^{-2} \cdot s^{-1}$] | % |
|---|---|---|
| Ultraviolet 300-399 nm | 86.6 | *79.6%* |
| Blue 400-499 nm | 14.4 | *13.2%* |
| Green 500-599 nm | 0.4 | *0.3%* |
| Red 600-699 nm | 0.5 | *0.4%* |
| Far-Red 700-799 nm | 1 | *0.9%* |
| Near Infrared 800-900 nm | 3.3 | *3.0%* |
| Total 300-900 nm | 108.8 | *100.0%* |
| PAR 400-700 nm | 15.2 | *14.0%* |
| YPF (photon-weighted) 300-800 nm | 62.9 | |
| PSS | (300-800 nm) | 0.71 |
| B/G | 420:490 nm / 500:570 nm) | 5 |
| R/FR | 640:680 nm / 710:750 nm) | 0.42 |
| Illuminance | [lx] | 66 |

## Sunlight at noon on a clear sky day




| | |
|---|---|
| Spectrometer: | JAZ - Ocean Optics (JAZA3088) |
| Date: | 2015-08-14 |
| Time: | 10:20:45 UTC |
| Place: | Vassbo, Sweden (60.528528° N, 15.524748° E) |

| Waveband | Photon flux density (PFD) [$\mu mol \cdot m^{-2} \cdot s^{-1}$] | % |
|---|---|---|
| Ultraviolet 300-399 nm | 92.8 | *4.1%* |
| Blue 400-499 nm | 366.4 | *16.2%* |
| Green 500-599 nm | 483.1 | *21.3%* |
| Red 600-699 nm | 491.8 | *21.7%* |
| Far-Red 700-799 nm | 424.5 | *18.7%* |
| Near Infrared 800-900 nm | 384.8 | *17.0%* |
| Total 300-900 nm | 2265.3 | *100.0%* |
| PAR 400-700 nm | 1355.2 | *59.8%* |
| YPF (photon-weighted) 300-800 nm | 1211.6 | |
| PSS | (300-800 nm) | 0.72 |
| B/G | 420:490 nm / 500:570 nm) | 0.8 |
| R/FR | 640:680 nm / 710:750 nm) | 1.1 |
| Illuminance | [lx] | 76572 |

## 3.3 Indoor cultivation

The trials here presented were done inside an indoor growth room with controlled environment at the forestry research station of Dalarna University in Vassbo, Sweden (lat. 60.528°; long. 15.524°; alt. 130 m).

During the germination phase (approximately the first week after sowing) the conditions were set to a $T_a$ of 20°C and an air relative humidity (RH) of 80 ± 10%. During the vegetative growth phase (about four weeks following germination), the RH was lowered to 60 ± 10%. The light intensity was adjusted to the desired PPFD according to the corresponding treatment, with a maximum variation of ± 10 $\mu mol \cdot m^{-2} \cdot s^{-1}$ over the entire growing area.

The spectra and intensity of the lamps was measured at the beginning and at the end of each trial to assure an even distribution. Twice a week, the irrigation was done by flooding the substrate in the trays until saturation. At the time of irrigation, the trays were also rotated one position clockwise to balance the growing conditions.

Depending on the study, the indoor cultivation period corresponded to:

- one week for germination phase and
- four weeks of vegetative growth (Papers I, II, III).

Followed by:

- five weeks of SD-treatments at different temperatures (Paper II), or
- one week for light shock mitigation treatment indoors (Paper III).

### 3.3.1 Light quality treatments

In order to compare the spectral effects of light quality produced by the different fixtures on the seedling development, two trays of mini-plug containers for each species and light treatment (Fluorescent, LED 1, LED 2, LED 3) were sown. The PAR intensity in all cases was kept constant at 100 ± 10 $\mu mol \cdot m^{-2} \cdot s^{-1}$ at substrate level. (Paper I).

### 3.3.2 Light intensity treatments

Based on previous studies with conifer species using artificial lights [31, 32, 48–52, 238], light intensities between 50-400 $\mu mol \cdot m^{-2} \cdot s^{-1}$ were chosen for the test. Only one promising LED spectrum (LED 3) was used based on the growth performance of the light quality tests. The PPFD in each treatment was adjusted to the double of the previous level, starting at 50, then 100, 200, and finally 400 $\mu mol \cdot m^{-2} \cdot s^{-1}$, with a maximum variation of ± 10 $\mu mol \cdot m^{-2} \cdot s^{-1}$. The light intensities were adjusted at substrate level before the sowing and measured again for control at the end of the growing period (Paper I).

### 3.3.3 Short-day (SD) treatments

The short-day (SD) treatments were chosen based on results of other previous studies that had used very young seedlings [110, 119, 141, 146]. They consist of a combination of two photoperiods (5 h in Sowing 1 and 8 h in Sowing 2) at three different temperatures (5°C, 10°C or 20°C) applied during five weeks.

Following the pre-cultivation phase, two trays of each species were placed in one of three growth room facilities set at one of the chosen temperatures with a RH of 60 ± 10%. The photoperiod treatment was replicated once within each growth room, with a PPFD of 100 ± 10 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and using only lamps of LED 3 spectrum. Following the SD treatments, the cold hardiness was assessed and the seedlings were transferred to a cold and dark storage at +2°C. Finally, after three months, the seedling vitality was tested (Paper II).

### 3.3.4 Light shock mitigation treatments (indoors)

The light shock mitigation treatments indoors started after the regular five weeks of pre-cultivation. The ambient temperature and relative humidity remained unchanged at 20°C and 60%. One tray of each species was randomly assigned to each of following different treatments (Paper III):

Control
- LED 3 spectrum at a PPFD of 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$
  with a photoperiod of 16 h (equivalent DLI of 5.8 $mol \cdot m^{-2} \cdot d^{-1}$).

High intensity
- LED 3 spectrum at a PPFD of 300 $\mu mol \cdot m^{-2} \cdot s^{-1}$
  with a photoperiod of 16 h (equivalent DLI of 17.3 $mol \cdot m^{-2} \cdot d^{-1}$).

UVA 30 min
- LED 3 spectrum at a PPFD of 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$
  with a photoperiod of 16 h (equivalent DLI of 5.8 $mol \cdot m^{-2} \cdot d^{-1}$)
  Simultaneously, 30 min daily exposure of UVA-LED spectrum at a PFD of 87 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (0.16 $mol \cdot m^{-2} \cdot d^{-1}$) (Sowings 1-2 in 2014)

UVA 60 min
- LED 3 spectrum at a PPFD of 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$
  with a photoperiod of 16 h (equivalent DLI of 5.8 $mol \cdot m^{-2} \cdot d^{-1}$)
  Simultaneously, 60 min daily exposure of UVA-LED spectrum at a PFD of 87 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (0.31 $mol \cdot m^{-2} \cdot d^{-1}$) (Sowings 1-2 in 2014)

UVA 240 min
- LED 3 spectrum at a PPFD of 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$
  with a photoperiod of 16 h (equivalent DLI of 5.8 $mol \cdot m^{-2} \cdot d^{-1}$)
  Simultaneously, 240 min daily exposure of UVA-LED spectrum at a PFD of 87 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (1.25 $mol \cdot m^{-2} \cdot d^{-1}$) (Sowing 3 in 2015)

## 3.4 Outdoor cultivation

After the indoor cultivation phase, the seedlings that were intended for outdoor cultivation were transplanted into multi-pot containers (Hiko V93, BCC AB; Landskrona, Sweden) of bigger dimensions (tray size: 352 x 216 mm; density: 526 seedlings per $m^2$; 40 cells per tray; volume per cell: 93 $cm^3$) filled with regular peat substrate (Närkes miljöproduktion AB, Sweden).

The trays were placed outside at the research station on elevated pallets. Automatic irrigation was done daily with approximately 7 litres per $m^2$ (about 0.5 L per tray). Fertilization was done manually twice a week, providing a weekly nitrogen supply of 3 $g \cdot m^{-2}$ (Wallco, Sweden) until the end of the vegetation period.

In the studies here presented, the term ‘transplanting’ refers to replanting mini-plug seedlings cultivated indoors into larger containers and immediately transferring them outdoors at the nursery for further cultivation. This differs from ‘outplanting’ which comprises the processes of transport, delivery and seedling planting a the reforestation site [239] (Paper I and III).

### 3.4.1 Forest field trial

In order to evaluate the performance and establishment in the field, 15 seedlings of each light quality treatment and species from the second sowing were randomly selected for a forest trial. After the outdoor cultivation at the nursery, the selected seedlings were divided into five subgroups of three seedlings each and outplanted in a clear-cut area during the autumn of 2013 (9th October) following a randomized block design [240].

The planting location represented the average soil (glacial till) and climate conditions of a forest planting site in mid-Sweden (lat. 60.56°; long. 15.48°). Stem height and diameter were measured at the end of each vegetation period during the three following years (on 26th September 2014, 3rd October 2015 and 5th October 2016) (Paper I).

### 3.4.2 Light shock mitigation treatments (outdoors)

The outdoor treatments for light shock mitigation consisted of a transient phase using a shading cloth. This technique could potentially reduce the stress and improve the acclimatization to the outdoor conditions [199]. Treated seedlings were first placed under a climate screen SOLARO 3320 (AB Ludvig Svensson, Kinna, Sweden) 50 cm above the seedlings during one or three weeks. The climate screen reduced the light intensity by 30% and has shown no major effects on the spectral composition underneath [200] (Paper III).

## 3.4.3 Outdoor temperature and solar radiation

The outdoor conditions ($T_a$, PPFD and UV $PFD_{250\text{-}400\,nm}$) were monitored during outdoor cultivation phase of the light shock mitigation experiments; corresponding to the vegetation periods of 2014 and 2015 (see Figure 3.1). The solar radiation was measured every minute using separate quantum sensors for PAR and UV (SQ-110 and SU-100, Apogee Instruments, Logan UT, USA). The ambient temperature was monitored using a weather station Vantage Pro2 (Davis Instruments, Hayward CA, USA) (Paper III).

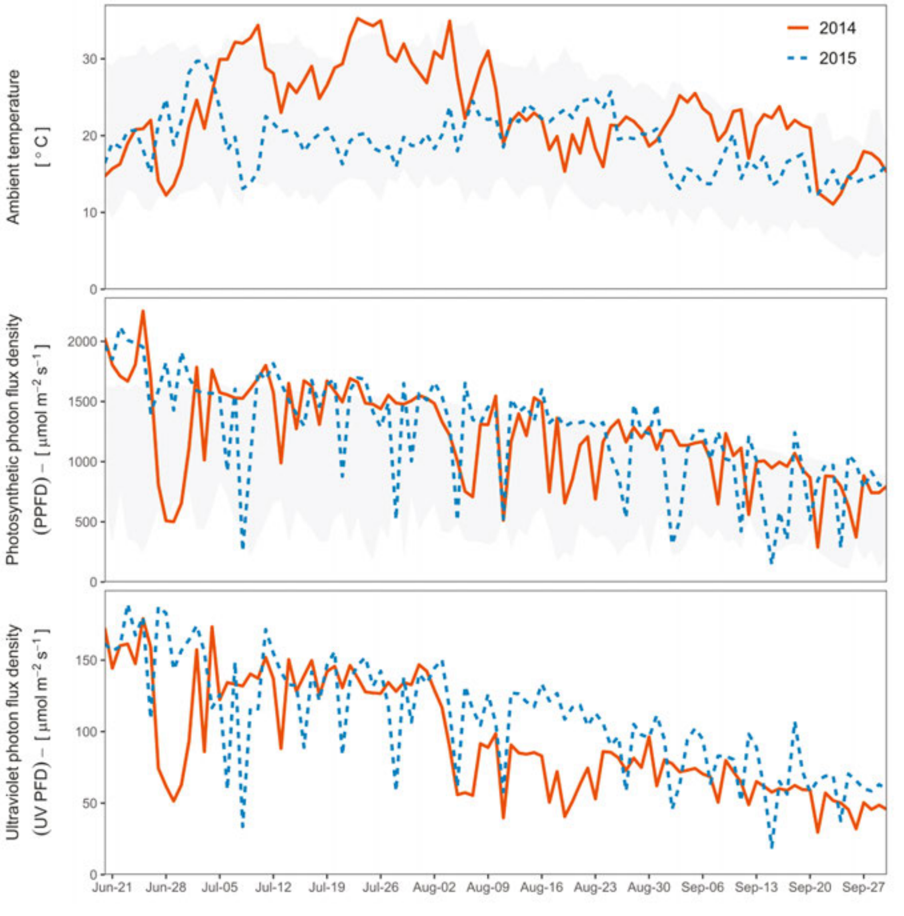



Figure 3.1: Ambient temperature (Ta, °C), solar PAR PPFD, $\mu mol \cdot m^{-2} \cdot s^{-1}$) as well as solar UV-radiation (UV $PFD_{250\text{–}400\,nm}$, $\mu mol \cdot m^{-2} \cdot s^{-1}$) during the vegetation periods of 2014 and 2015 at the research station in Vassbo, Sweden (lat. 60.53°; long. 15.53°). The lines for the corresponding years indicate the maximum daily values measured at the station while the grey bands show the range of historical values reported by the Swedish Meteorological and Hydrological Institute (SMHI) [241, 242] (see Paper III).

## 3.5 Seedling assessment

Seedling quality, described as ‘fitness for purpose’ [243], requires aligning the cultivation strategies towards the main goal which, for anyone producing forest seedlings, is survival and establishment in the field [244]. There is no single index that can alone predict seedling performance and definitively none than can guarantee success in the field. Instead, cultivation frameworks such as the ‘target plant concept’ [245] rely on a evaluating a combination of material attributes (single point measurements of specific subsystems) for fast assessments, and performance attributes (integrated response of several subsystems) to deliver the best suited seedlings for planting site [244, 246].

### 3.5.1 Morphological attributes

The morphological characteristics measured during these trials were the shoot height and stem diameter (mm), as well as shoot and root dry weight (DW, g). The DW samples were dried in an oven for 24 hours at 100°C and then placed in a desiccator another 24 hours before weighing. The seedling quality was assessed based on the individual values as well as the ratios; considering the height:diameter ratio as a sturdiness parameter, and their shoot:root ratio as the balance between their photosynthetic and transpirational zone (shoot system) against their nutrient and water absorbing zone (root system) [247].

### 3.5.2 Root growth capacity

In order to evaluate the vitality of the seedlings, a root growth capacity (RGC) test was performed prior to the field trial for the various light qualities (Paper I); following indoor pre-cultivation under different light intensities (Paper I); and after three months of storage in dark at +2°C for the different SD-treatments (Paper II). The test was carried out following the methodology and using the setup and equipment described in [248, 249].

The seedlings were randomly selected for testing and transplanted into separate containers placed in stainless-steel trays filled 1:1 with sand and peat. The substrate temperature was controlled by placing the stainless-steel trays in a water bath kept at 20 ± 1°C. The seedlings were grown in the RGC-bath for 21 days at an air temperature of 20 ± 1°C, a RH of 60 ± 5%, a photoperiod of 16 h and a PPFD of approximately 300 $\mu mol \cdot m^{-2} \cdot s^{-1}$ provided by HPS lamps. Afterwards, the containers with the seedlings were carefully taken out of the stainless-stell trays. All the newly formed roots were cut, cleaned and dried in an oven at 100°C during 24 h and then placed in a desiccator for another 24 h to obtain the dry weight of the new grown roots.

### 3.5.3 Chlorophyll fluorescence

Chlorophyll fluorescence (ChlF) is a technique used to obtain a better understanding on the status of the Photosystem II (PSII) and gives insights on the photochemical reactions in plants [250]. PSII is the first protein complex in the light-dependent reactions of photosynthesis; responsible for capturing photons and splitting water into hydrogen ions and molecular oxygen [66].

In the studies here reported, the seedlings were dark-adapted during at least one hour and measured on the top part of the shoot of as described by [251] using a portable Chlorophyll Fluorometer FMS 2 (Hansatech Instruments, UK). The maximum quantum yield of the PSII was calculated as the ratio of the variable ($F_v$) and maximum ($F_m$) chlorophyll fluorescence ($F_v/F_m$) considering the dark adapted state ($F_0$) as the baseline [66]:

$$\frac{F_v}{F_m} = \frac{(F_m - F_0)}{F_m} \tag{9}$$

In applied forestry, ChlF has been suggested as a good estimator for seedling stress and as a possible performance estimator in the field [252, 253]. Although this non-destructive method is mainly used for detecting cellular damage after freezing storage [254, 255]; it also allows finding injuries on the photoreceptors caused by excessive radiation [256] (Paper I and III), and has been proposed as an indicator of seedling cold hardiness [257–260] (Paper II).

### 3.5.4 Photosynthetic light-response curves

Excessive radiation can cause photodamage on the photoreceptors of the seedlings, ultimately resulting in lower photosynthesis and a reduced $CO_2$ uptake [188]. In order to assess the health of the seedlings' photosynthetic apparatus, the net $CO_2$ assimilation at different light intensities was measured and the average photosynthetic light-response curves were calculated. This was done both for seedlings pre-cultivated at different PPFD levels (Paper I), as well as for seedlings transplanted to direct sunlight exposure (Paper III).

The light-response curves were measured using an open gas exchange system CIRAS-3 (PP-Systems, USA) equipped with the PLC3 Conifer Cuvette (Part No. CRS302). The equipment provided decreasing levels of PPFD until reaching darkness, maintaining the conditions for at least 5 min to allow seedling acclimation [261]. The $CO_2$ concentration in the cuvette was 390 $\mu mol \cdot mol^{-1}$ with an air flow of 300 $mol \cdot s^{-1}$ at 20°C and RH of 60%. As it was done in [262–264], the net $CO_2$ uptake was calculated as function of the needles dry mass ($\mu mol\ CO_2 \cdot kg^{-1} \cdot s^{-1}$) instead of using projected needle area.

## 3.6 Storability assessment

Finding effective treatments for the induction of cold hardiness is crucial for the success of the year-round pre-cultivation concept. For this reason, different assessment methods were used based on what has been reported as promising tests for identifying cold hardiness in very young forest seedlings [146, 255, 259, 265, 266] The methods were also chosen according to their potential applicability in industry [244, 246]. This would make them suitable for future implementation in commercial nurseries that decide to implement the concept in their standard operations.

The following tests were used for measuring the effectiveness of the treatments in inducing cold hardiness prior to seedling storage:

- Chlorophyll fluorescence [252, 258, 259] (as previously described)
- Shoot electrolyte leakage [120, 146, 265, 267, 268]
- Gene expression of cold tolerance markers [269–271]

After 3 months of storage at +2°C, the seedlings' vitality was evaluated with:

- Root growth capacity test [248, 249] (as previously described)

### 3.6.1 Shoot electrolyte leakage

Freezing tolerance can be a reliable indicator of cold hardiness, particularly for the shoot system. In principle, it consists in measuring the degree of intracellular damage present after exposing the seedling to sub-zero temperatures [255, 259]. The ice crystals that form in the cells during freezing can produce damage to the tissue and this is quantifiable by calculating the amount of electrolytes that escape the cell membranes [272].

Measuring the electrolyte leakage (EL) from the root system can be challenging and lead to wrong conclusions [273–275]. For this reason, only the shoot electrolyte leakage difference ($SEL_{diff}$) was measured; following the method described by [268, 276] recently updated in [146, 265].

In contrast to the original method where only the top of the shoot is used, due to the small size of the seedlings in this study, the complete shoot was cut and placed in plastic bottles. Each plastic bottle contained the full shoot of five seedling, considered a subsample, with five subsamples per treatment. To account for the natural leakage of cells, one subsamples per treatment was saved unfrozen as control in a cooler at +5°C. The other four subsamples were placed into a programmable freezer that gradually reduced the temperature at an hourly rate of -2.5°C until the target temperature (-10°C or -25°C) was reached and maintained for one hour. Finally, the samples were thawed slowly at a similar rate until reaching +5°C. For the lowest target temperature, the total duration of the test was approximately 28 hours.

After the freezing and thawing routine, deionized water (40 ml) was added to all of the bottles which were then shaken for 24 hours. The electrical conductivity (EC) in each bottle was measured using a portable conductivity meter Hach SensION 5 (Hach Company, Loveland CO, USA). The total amount of electrolytes from the shoots was obtained by autoclaving them for 10 min at 120°C and 1.2 bar. A second electrical conductivity measurement for each bottle was made after boiling ($EC_{boiled}$). The shoot electrolyte leakage (SEL, %) was calculated as the ratio between the electrical conductivity before and after boiling of each subsample (including the control) [265]:

$$SEL_T = \frac{EC_T}{EC_{boiled}} \times 100 \quad (10)$$

Where the subscript 'T' can either be the target temperature at which the subsample was frozen (-10°C or -25°C), or 'control' for reference subsamples.

Finally, the test parameters ($SEL_{diff,\,T}$) were calculated as the differences in leakage between the unfrozen ($SEL_{control}$) and frozen ($SEL_T$) seedlings:

$$SEL_{diff,T} = SEL_T - SEL_{control} \quad (11)$$

### 3.6.2 Gene expression of cold tolerance markers

The freezing tolerance and storability status was also determined using the molecular test ColdNSure™ (NSure, Wageningen, The Netherlands) [120, 265]. This test quantifies the relative amount of certain molecules called messenger RNA (mRNA) that are produced during the process of transcription when a gene becomes active. For Norway spruce the test measures the specific upregulated expression of the genes PaCO4 and PaCO8 and for Scots pine the molecular indicators used are Ind1 and Ind2 [269–271].

After the SD-treatments, the shoot tips of 15 seedlings per treatment and species were prepared as described by [146, 265]. The samples were then sent to the NSure laboratory (Wageningen, The Netherlands) for testing. The laboratory reported the results as relative gene expressions after using the Delta-Delta cycle threshold method (ddCt) together with the corresponding cold tolerance status according to a 4-phases scale of the test [120]:

0. Cold sensitive: the profile corresponds to that of seedling that are actively growing with no sign of cold tolerance development.
1. Developing cold tolerance: early signs of frost tolerance development can be recognized.
2. Developing cold tolerance: level approaches full cold tolerance.
3. Cold tolerant: the profile matches that of seedlings that have ceased growth and that are fully cold tolerant, ready for lifting and storage.

## 3.7 Supplementary lighting requirements

### 3.7.1 Data sources

The ambient temperature and solar radiation maps (including DLI), as well as the supplementary lighting calculations and photovoltaic yield estimations were done based on meteorological data publicly available from the European Commission Joint Research Centre JRC) in Ispra, Italy. These were accessed through their online service Photovoltaic Geographical Information System (PVGIS) version 5.1 [147, 231].

The data used corresponds to a reanalysis made by the European Centre for Medium-range Weather Forecast (ECMWF-ERA-5) which contains hourly values for the period of 2005 - 2016 at a spatial resolution of 0.25° (latitude and longitude) with approximately 30 km global grid [277, 278]. In spite of higher uncertainties, ECMWF-ERA-5 provides data for the Nordic regions where geostationary satellites have normally no cover. For this reason, it is suggested in PVGIS as the default source for northern latitudes [147].

The values were obtained via the non-interactive service of PVGIS for the region between latitude 54.5° - 70.0° N and between longitude 4.5° - 31.5° E, using a grid cell of 0.1° × 0.1° in both geographic coordinates. In total, 33051 points were retrieved without counting locations over the ocean. The cells in this study were selected of the same angular distance (0.1° × 0.1°) as those reported in similar maps of the United States [77] to allow comparability.

For each location, the meteorological data consisted of hourly averages of a representative day for each month (i.e., for every hour in the day, the average was calculated from all the days in that month and from all years available). This resulted in 24 values for each of the 12 months at each location (288 values in total for the year). The meteorological variables extracted were:

- Global, direct and diffuse horizontal irradiance ($G_h$, $G_b$, $G_d$; $W \cdot m^{-2}$)
- Ambient temperature at 2 m above the ground ($T_a$, °C).

PVGIS was also used to estimate the monthly energy output of different PV system configurations (see Table 3.2) using the same geographical grid and radiation data source. For each location and configuration, 12 monthly energy output values ($E_{PV}$, $kWh \cdot mo^{-1}$) were obtained. The following parameters were used for all system configurations and locations:

- $P_{PV,\,STC}$: 6 kW;
- PV technology: crystalline silicon (c-Si);
- mounting position: fixed and building-integrated;
- horizon: yes;
- estimated system losses: 14% (*PVGIS default*).

### 3.7.2 Lighting control protocols

Two lighting control protocols previously established were compared: on-off control vs. adaptive control [168, 169]. The calculations were done for the entire geographical grid during an assumed greenhouse cultivation period of 181 days: from February 1st to May 20th and from August 20th to October 31st of an average year. Dimmable LED fixtures were considered as the supplementary lighting source used to maintain a minimum PAR level ($PPFD_{threshold}$) throughout a photoperiod of 16 $h \cdot d^{-1}$.

The PAR transmitted inside the greenhouse ($PPFD_{GH}$) was a function of the irradiance outdoors ($PPFD_{Sun}$, using Equation 4) and assuming a reasonable value for $\tau_{h, PAR}$ (40%, 55% or 70%):

$$\begin{aligned} PPFD_{GH} &\approx \tau_{h,\,PAR} \cdot PPFD_{Sun} \\ &\approx \tau_{h,\,PAR} \cdot \left(G_h \cdot (0.45)(4.484\ \mu mol \cdot Ws^{-1})\right) \end{aligned} \tag{12}$$

For both protocols, when the natural light transmitted inside the greenhouse reached or surpassed the threshold ($PPFD_{GH} \geq PPFD_{threshold}$), then the lamps would turn off and emit no light ($PPFD_{lamps} = 0$).

However, if the threshold was not reached ($PPFD_{GH} < PPFD_{threshold}$):

- With the on-off control protocol, the lamps would have an output exactly at the threshold level. This would be equivalent of having lamps with a fixed output (e.g., HID lamps), and just switching them on and off when required.
- In contrast, the adaptive control protocol takes advantage of the dimmability of the LED fixtures. The output of the lamps is assumed to be continuously adjusting and provides only the difference necessary to reach the desired threshold.

Equations 13 and 14 below summarize the control protocols (Paper IV):

$$PPFD_{lamps,\,on-off} = \begin{cases} 0, & PPFD_{GH} \geq PPFD_{threshold} \\ PPFD_{threshold}, & PPFD_{GH} < PPFD_{threshold} \end{cases} \tag{13}$$

$$PPFD_{lamps,\,adaptive} = \begin{cases} 0, & PPFD_{GH} \geq PPFD_{threshold} \\ PPFD_{threshold} - PPFD_{GH}, & PPFD_{GH} < PPFD_{threshold} \end{cases} \tag{14}$$

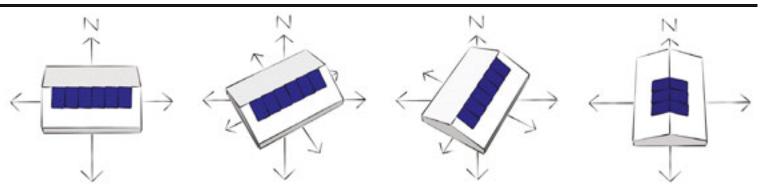
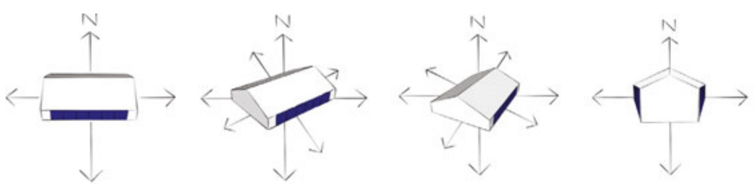
## 3.8 Photovoltaic systems in forest nurseries

It was assumed that the PV modules were integrated in the structure of a wide-span greenhouse with a double-pitched roof which are typical in northern Europe [24, 279]. The GHIPV was supposed to be installed either on the roof (25° slope) or on the wall (90° slope) of the greenhouse.

The shading effect of different coverage ratios would ultimately determine the PV system size for a particular roof area. Instead of calculating multiple $PV_R$ and optimizing the shading effect to a particular PV system size, which in turn would need to be validated for the light needs of each plant species; an arbitrary $P_{PV, STC}$ of 6 kW was chosen for all locations and configurations. The reason was that this amount can be easily distributed along the different roof orientations using whole number ratios (6:0, 5:1, 4:2, 3:3) and these systems can be latter scaled to larger sizes once the actual $PV_R$ is decided.

The monthly average energy production extracted from PVGIS was combined into the yearly total output ($E_{PV}$, kWh·yr$^{-1}$). Finally, the total $E_{PV}$ was divided by the $P_{PV, STC}$ of 6 kW to obtain the specific energy yield relative to that installed power ($E_{rel,PV}$, kWh·kW$^{-1}$·yr$^{-1}$) (Paper IV).

Table 3.2: Orientation and nominal peak power of PV systems analyzed

| **Roof mounted systems** *slope: 25°* |  | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| orientation | N — | S | NW — | SE | NW — | SE | W — | E |
| azimuth | 0° | 180° | 330° | 150° | 300° | 120° | 270° | 90° |
| $P_{PV, STC}$[1] | | 6 kW | | 6 kW | | 6 kW | 3 kW | 3 kW |
| **Wall mounted systems** *slope: 90°* |  | | | | | | | |
| orientation | N — | S | NW — | SE | NW — | SE | W — | E |
| azimuth | 0° | 180° | 330° | 150° | 300° | 120° | 270° | 90° |
| $P_{PV, STC}$ | | 6 kW | | 6 kW | | 6 kW | 3 kW | 3 kW |

[1] Additional configurations with $P_{PV, STC}$ distributed among the NW – SE roofs are in Paper IV.

## 3.9 Data analysis

The data analysis for the different studies was performed mainly using the statistical software R (different versions) [280] using the *tidyverse* package collection for raw data manipulation [281, 282]. When possible, the results from the different studies were visually presented following an 'RDI principle', showing the individual raw data, descriptive and inferential statistics in one single plot [283, 284].

The spectral analysis of the light sources was done using the *r4photobiology* suite [164] and the corresponding methods for photobiology calculations in R [236] (Paper I, III). The geographical vector data for the maps of the different regions (Paper IV) was retrieved from the public dataset Natural Earth [285] using the package *rnaturalearth* [286] and plotted using *ggplot2* [287, 288] and *sf* packages [289, 290] (Paper IV).

Since the LED lamps tested were prototypes and only one set of luminaries was available, strictly speaking it was not possible to have true replicates for most of the trials. This situation is a well-known issue when using expensive or rare equipment and the specific problematic for the case of growth chambers and greenhouses has been vastly discussed [291–293]. In order to address this issue and test the repeatability of those results with lack of true biological replicates, the experiments were repeated for at least two sowings (becoming 'unreplicated repetitions' [294]).

To facilitate comparability with other equipment, two LED lamps of each type were thoroughly measured and the spectral profiles are fully reported as suggested in literature [235]. The environmental conditions during cultivation were constantly monitored and all the biological experiments were done with the same set of lamps and using the same growth room facilities. Additionally, all sowings were done with seeds from the provenances and batches as well as using identical trays and substrate composition.

In those cases where inferential statistical analysis was possible, the sowings were treated as 'blocks in time' as well the experimental units (repeats instead of replicates) [283]. The individual seedlings were then considered the observational units within each sample and used to estimate the sampling error [295]. In methods where several seedlings were measured at once (e.g., DW, RGC, SEL), the value of this subsample was considered the observational unit [296] and the subsamples of each treatment were averaged to avoid pseudoreplication [297].

Light quality and light intensity treatments (Paper I)

- The analysis was performed using a randomized complete block design with subsampling, and regarding the separate sowings as 'blocks in time', with each light treatment present exactly once per block. The repetitions in time (sowings) were used to account for variations and random fluctuations in the growth room following the example in [298] with the methodology by [296]. The relationship between the results of the different methods was calculated using Pearson's correlation coefficient (r).
- Although the field trial followed a randomized block design as in [240], the lack of replication of the main factor (light quality, using only sowing 2) prevented further inferential testing [299].

Short-day treatments (Paper II)

- The statistical testing followed a linear mixed effects model with a nested design (nested ANOVA) with subsampling [300, 301] using the R package *nlme* [302]. The temperature factor was nested within the blocks (sowing) while the photoperiod was confounded with the with the block (Sowing 1: 5 h, Sowing 2: 8
- The estimated marginal means (EMMs, also known as least square mean) were used to analyze the ChlF measurements followed by a post-hoc Tukey test using the R package *emmeans* [303].
- Due to the destructive character of the RGC and SEL methods; seedlings from both replicated per sowing were pooled together before randomly selecting the subsamples for each of these tests. This decision of aggregating the results and effectively sacrificing replication in exchange for a higher measurement precision restricted the possibility of performing inferential testing. However, it allowed a more thorough assessment that revealed the most information [283, 304] and still allowed the comparison with the other methods using Pearson's correlation coefficient (r).

Light shock mitigation treatments (Paper III)

- The ChlF data of the light shock mitigation treatments was analyzed as a repeated measures ANOVA with the methodology described by [301, 305] in order to study the effects of the treatments within subjects. The R package *nlme* [302] was used to generate a mixed effect model with both a random intercept and a random slope for each treatment to explicitly model the changes in ChlF for individual seedlings over time.

Lighting control protocols and energy requirements (Paper IV)

- In order to support reproducibility of the results from the supplementary lighting requirements and photovoltaic system calculations, only data with open access (PVGIS, ECMWF-ERA-5, Natural Earth) and open-source software (R and corresponding packages) was used. The equations and procedures required are reported in the corresponding sections.

# 4 Results and discussions

## 4.1 Light quality treatments

The feasibility of using LED lamps as a photosynthetic light source for seedling cultivation was tested as a first step in these trials. There were no statistically significant differences in the measurements of shoot height or stem diameter among the various light quality treatments for either of the species. The sturdiness presented average values close to 40:1 for the height-to-diameter ratio in all treatments and for both species.

The biomass distribution was also similar regardless of treatment or species, with a shoot-to-root ratio between 3:1 and 5:1 (see Figure 4.1). Although the proportions remained, the trend showed that seedlings pre-cultivated under fluorescent lights presented lower shoot and root dry weights compared to those that had been growing under LED lights. This could also be a consequence of the radiative heat emitted by the fluorescent lamps affecting the cultivation area. For both Norway spruce and Scots pine, LED 2 and LED 3 produced seedlings with significantly higher shoot dry weights ($p < 0.001$) compared to the fluorescent lamps.

Comparing the LED treatments, the differences were small but with a trend to better development for seedlings cultivated under LED 2 and LED 3 in comparison to LED 1. This could be a result of spectral differences (Table 3.1) since stem elongation and needle expansion are favored by red and far-red photons while blue and green photons promote plant compactness [47, 52, 96].

However, even if it may not be critical for development, a certain amount of blue and green light can help the human eye to distinguish colors and reduce discomfort when working in growth room facilities [36]. Since the LED 3 spectrum showed a good performance during cultivation and only minor eyestrain compared to LED 2, it was chosen for the rest of the trials.

In general, the results of the light quality tests showed that after five weeks of pre-cultivation under any of the LED spectra, both Norway spruce and Scots pine seedlings had equal or better development in the attributes measured, compared to those grown under fluorescent lights. These results support the idea of LED lamps as a viable alternative to conventional light sources for seedling cultivation, being consistent with similar studies [46–49].

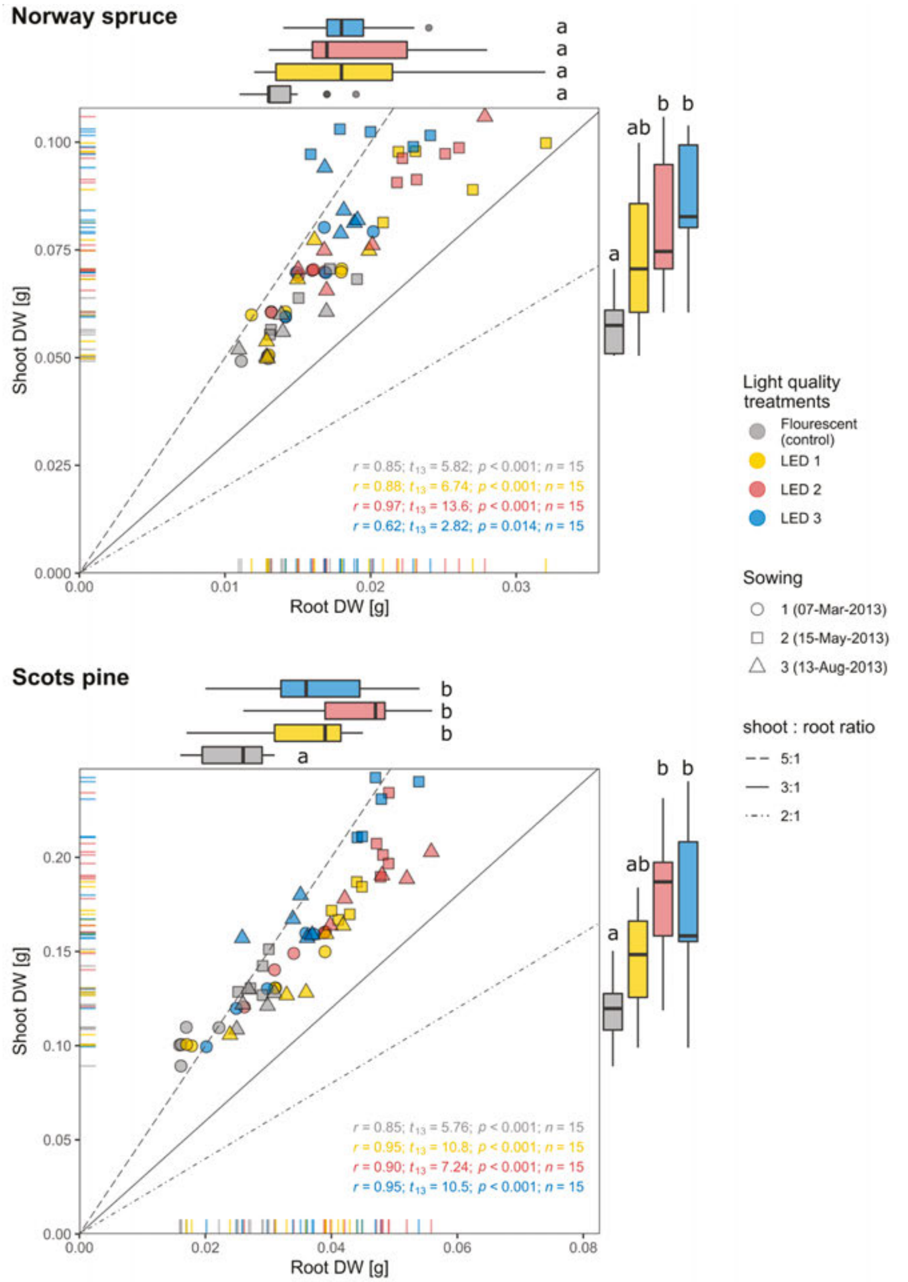



Figure 4.1: Biomass distribution as function of the shoot and root dry weight ratio of Norway spruce and Scots pine seedlings pre-cultivated under four artificial light spectra. Data presented as individual points per subsample (5 seedling per subsample, with 5 subsamples per sowing and treatment) including Pearson correlation coefficient (r) between shoot DW and root DW for all sowings (n =15). Marginal boxplots per attribute with small letters showing significant differences on the blocked comparison (n = [3 sowings × 4 treatments], $p < 0.001$) with an $F$-test. (see Paper I).

### 4.1.1 Forest field trial

The field trial showed only minor variations in seedling performance after three vegetation periods. Most of the observed differences in material attributes, which had been credited to the light quality treatments, appear to have been leveled out once the seedlings were out in the field (see Figure 4.2). As other studies have also shown, light spectra during indoor pre-cultivation may be of less importance for a successful establishment of forest seedlings, providing that healthy plants are produced [48]. Field stress and subsequent growth seem to compensate for quality differences, even if clear variations in performance attributes are measured at the nursery [249].

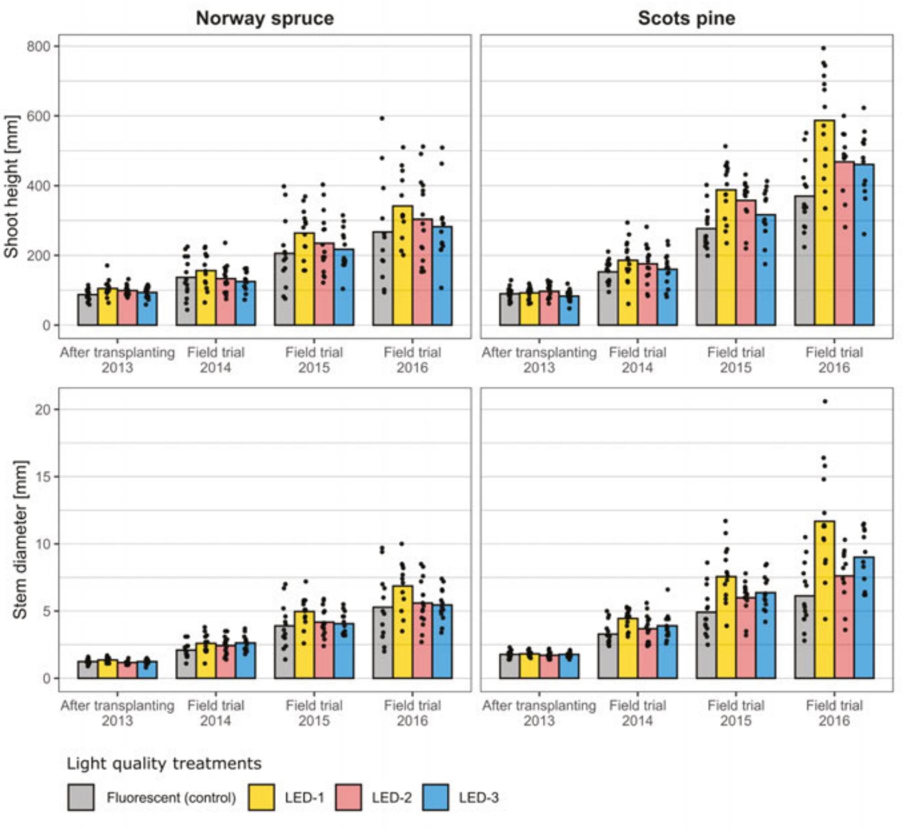



Figure 4.2: Shoot height and stem diameter for Norway spruce and Scots pine seedlings after outdoor cultivation during one vegetation period at the nursery (measured on 9th October 2013) as well as at the end of three vegetation periods in the forest field trial (measured respectively on 26th September 2014, 3rd October 2015 and 5th October 2016). The bars show treatment grand means while the dots present the values for the individual seedlings (see Paper I).

## 4.2 Light intensity treatments

The capacity of a tree to grow and compete under low light conditions is known in forestry as 'shade-tolerance' [306]. Norway spruce has low light requirement and can develop naturally under the canopy of sheltered woods; thus, it is considered a shade-tolerant tree species. On the other hand, Scots pine is a pioneer and shade-intolerant species that can establish without problems under full sunshine in clear site and after forest fires [264, 307]. These fundamental differences among the two tested species are reflected throughout the results of the light intensity treatments (see Figure 4.3).

After the trials, the results for both species indicated an inverse relationship between PPFD level and shoot elongation; with shorter seedlings developing under higher light intensities. Conversely, the shoot dry weight of both species as well as the root dry weight for Scots pine significantly increased ($p < 0.05$) at higher PPFD levels. It can be assumed that the main contribution to the shoot dry weight derived from the needles since there were no significant differences in stem diameter.This morphological phenomenon has also been observed in horticulture, where plants growing under insufficient light tend to develop elongated and water saturated stems. While those under higher light intensity increase their biomass production, resulting in compacter and heavier plants with more leaves [308–310].

During shoot growth, various morphological adaptations to light take place, including structural changes in needle size, needle distribution along the stem and stomatal density [190]. These changes aim to regulate the radiation flux, either by absorbing as many photons as possible in low light environments or by scattering them to the lower needles and avoiding photodamage [311].

Seedlings of both species grown under lower light intensities had fewer needles arranged in a flat 'umbrella' structure, and these were of a dark green colour. In contrast, the needles of seedlings cultivated under the higher PPFD levels were arranged closer together and had a yellowish colour (starting at 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for Norway spruce and at 400 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for Scots pine). A possible explanation for the colour difference could be a light shock stress caused by the high intensity which can scorch the needles and reduce the chlorophyll content [195].

Signs of light stress were also observed with the ChlF measurements. These were more pronounced for Norway spruce where a significant ($p < 0.05$) decrease in the maximum quantum yield of the PSII ($F_v/F_m$) occurred already at a PPFD of 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$. For Scots pine, the decrease only became significant until 400 $\mu mol \cdot m^{-2} \cdot s^{-1}$. However, it is important to mention that even though the drops in $F_v/F_m$ were statistically significant, the levels were still within the acceptable range considered for healthy plants [250, 251].

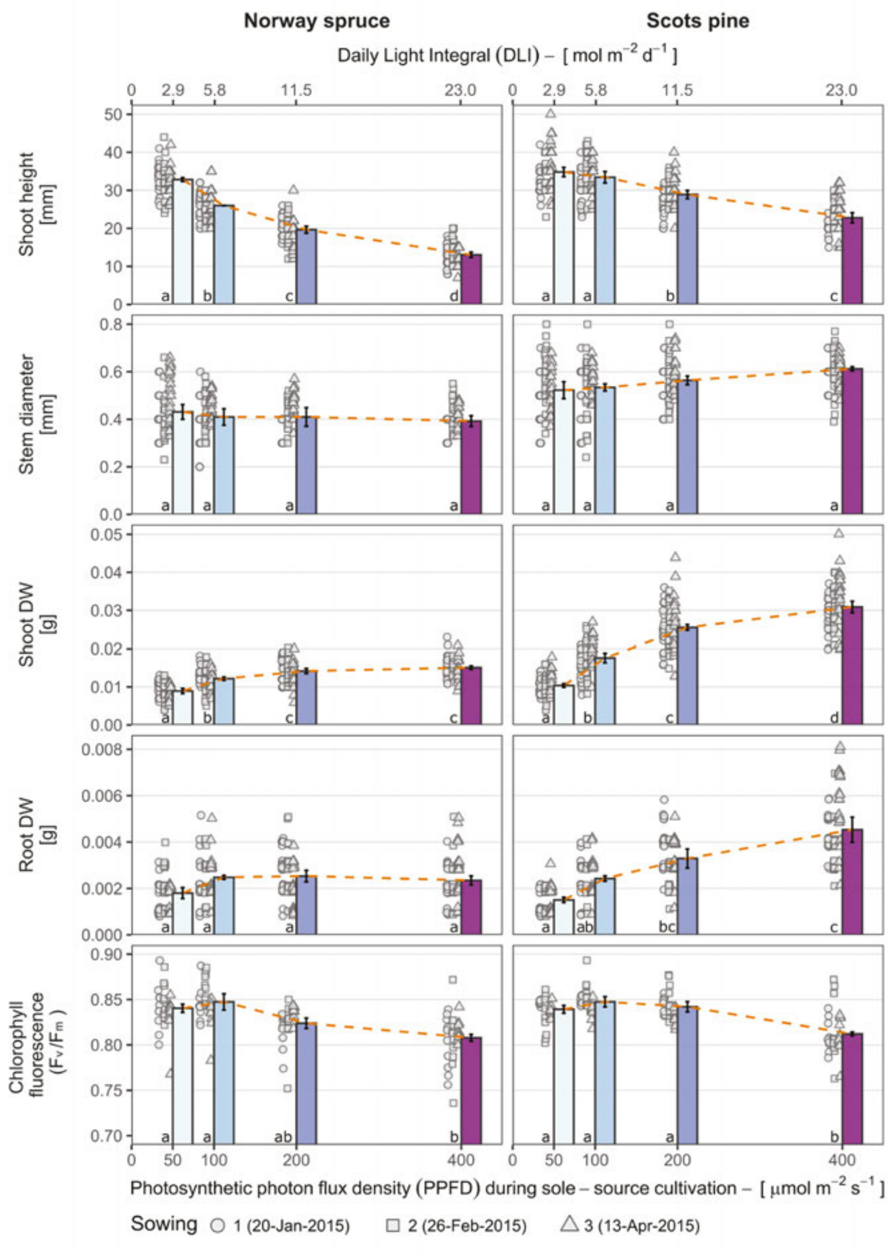



Figure 4.3: Morphological measurements and chlorophyll fluorescence for Norway spruce and Scots pine seedlings pre-cultivated under four different PPFD. Results presented as individual data points; a bar for the treatment grand mean, standard errors as vertical lines and a dashed orange trend line. Different letters show significant differences (n = [3 sowings × 4 treatments], $p < 0.05$). for the *F*-test (see Paper I)

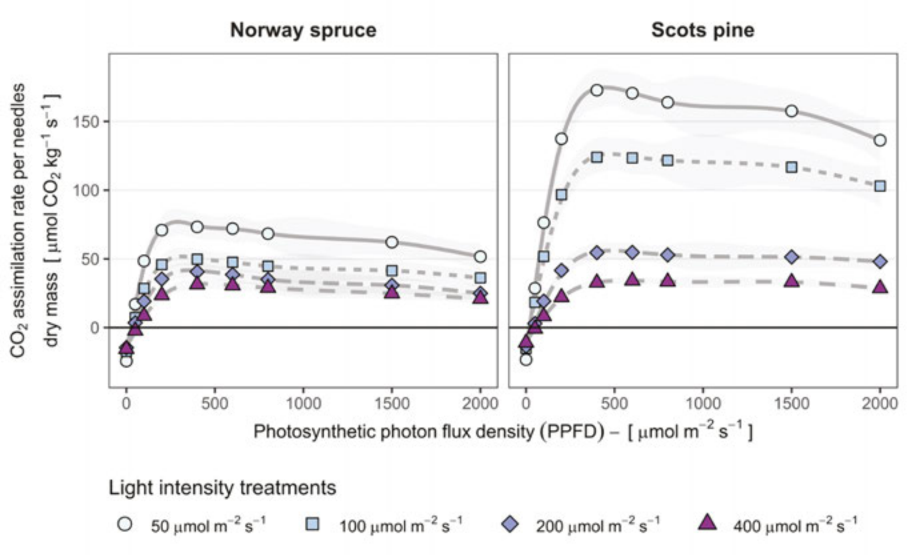



Figure 4.4: Light-response curves for Norway spruce and Scots pine seedlings pre-cultivated under four different PPFD. The net $CO_2$ assimilation was calculated relative to seedling's needles dry mass as a function of the light intensity; measured at a reference air $CO_2$ concentration of 390 µmol mol$^{-1}$ and 60% relative humidity. Each line presents the average of 3 seedlings per treatment per sowing (n = 9) while the shaded region shows the standard error of the sample mean (see Paper I).

When measuring the light response curves based on the needles dry mass, seedlings cultivated under lower PPFD levels showed higher $CO_2$ assimilation rates compared to those grown at higher intensities (see Figure 4.4). This corresponds with other studies using mass-based gas-exchange measurements [264, 312] and agrees with the notion that seedlings accustomed to low light environments will be prone to absorbing as much as light as possible. Although this may seem beneficial at first, not being able to deflect excessive light could be a weakness when exposed to full sunshine (see Paper III).

In all treatments, the light response curves of Norway spruce reached the light-saturation point where the intensity does not increase the assimilation rate of $CO_2$ at approximately 200 µmol·m$^{-2}$·s$^{-1}$. On the other hand, being a shade-intolerant species, this occurred above 300 µmol·m$^{-2}$·s$^{-1}$ for Scots pine.

The fact that plant growth behaves in a non-linear fashion with respect to the PPFD, in contrast to the electricity consumption, offers a great potential for optimization. The measurements of the LED lamps showed barely any spectral change while diming between the maximum to the minimum output (see Paper I). This property allows for a precise PPFD control of the lamps while maintaining a constant distance to the seedlings and efficiently utilizing the vertical space without influencing the spectrum.

## 4.3 Short-day treatments

Cold hardening is an energy demanding process where the seedlings not only must prepare to withstand the cold temperatures but also need to create carbohydrate reserves that last until the next vegetation period [133, 137, 143, 144]. The results of the study support this concept; agreeing with others that too short photoperiod [130], insufficient light intensity [313, 314] or too brief SD-treatment lengths [119–121] may fail in properly inducing cold hardiness. Besides the correct amount and duration of light, low temperature is a key factor, especially for Scots pine seedlings [118, 148, 315–317] (Paper II).

The chlorophyll content in woody species decreases during the autumn as the photoperiod shortness and the temperatures drop [318, 319]. In some cases, ChlF can be used as a measure to track these seasonal changes [259, 320]. The measurements in this study done on unfrozen seedlings confirmed significant differences ($p < 0.05$) in ChlF between the temperature treatments for both species. However, interpreting these results alone could lead to erroneous conclusions, particularly for the case of very young seedlings. For example, the reduction in $F_v/F_m$ could be a sign of injuries on the PSII caused by the treatment itself and not a consequence of a cold acclimation process.

In order to make a more adequate assessment, it has been recommended to measure the ChlF on frozen samples instead and combine these with another well-established method that also requires freezing (e.g., $SEL_{diff}$) [259]. The results from $SELd_{iff}$ and ChlF on frozen samples have shown to be highly correlated despite measuring cellular damage on different membrane systems [255]. Moreover, both $SEL_{diff}$ and ChlF are relatively fast methods (compared to RGC) and modern devices can make testing even more efficient.

The $SEL_{diff}$ in this study was measured for two target temperatures: -10°C and -25°C. For $SEL_{diff\text{-}10}$, the results correlated well with the RGC test after three months ($r < -0.9$). The SD-treatments at lower ambient temperatures (5°C and 10°C) noticeably improved the freezing tolerance down to -10°C, especially for Scots pine, with $SEL_{diff\text{-}10}$ values below 4%. In contrast, the results for $SEL_{diff\text{-}25}$ presented no clear pattern among the treatments. This could be a sign that these very young seedlings are not suited for freezing down to -25°C, resulting in a totally collapsed cell membrane [268, 276].

The relative gene expression levels (ddCt) as well as the RGC results, especially for Scots pine, followed a decreasing trend with increasing SD-treatment temperature (inversely correlated to the $SEL_{diff}$ measurements). Even though the differences were smaller for Norway spruce, the pattern was the same. The frost tolerance level, based on the ColdNSure™ scale, was the highest for Scots pine seedlings that received five hours of light at 5°C.

A safety limit of 4% for the test parameter $SEL_{diff\text{-}25}$ is commonly used when evaluating the freezing tolerance of conventionally cultivated seedlings [265]. However, no concrete safety thresholds for a target temperature of -10°C ($SEL_{diff\text{-}10}$) in very young seedlings have been found at the time of writing. Recent studies have highlighted the need for new or adapted methods for these cases [146]; particularly if seedlings are intended only for short periods of cold storage (about three months) at non-freezing temperatures (3° ±1°C) [141]. In these cases, there is evidence that the safety threshold could be raised without increasing the risk of damage [146].

Simultaneously comparing the results of different methods allowed for a better understanding of the cold hardiness process (see Figure 4.5). Lower temperatures and shorter photoperiods reduced the chlorophyll levels (ChlF) and increased the gene activity (ddCt), which in turn resulted in lower intracellular damage after freezing ($SEL_{diff-10}$). This apparent freezing tolerance down to -10°C was then matched by a higher seedling vitality (RGC) after three months of storage. However, since no freezing test was performed on the roots, it is not possible to tell if there was any root damage. In order to guarantee a successful introduction of the year-round cultivation concept, root freezing tests specially developed for very young seedlings are needed [146].

The duration of the SD-treatment could potentially be reduced from five to three weeks as proposed in [141], saving 40% of the energy for lighting. However, during this optimization process, it is important to find a balance that provides enough time for the cold hardiness to develop and enough radiation to allow sufficient carbohydrate reserves to form.

Finally, maintaining the proper air temperature and humidity levels in a growth room facility can account for more than 20% of the energy demand [171, 174]; and the lower temperatures required for the SD-treatments could potentially increase this. Although some examples already exist in the literature [27, 172, 321, 322], more studies that investigate the electrical and thermal energy requirements are necessary for a successful implementation of a year-round concept under LED-lamps in the boreal forest region.

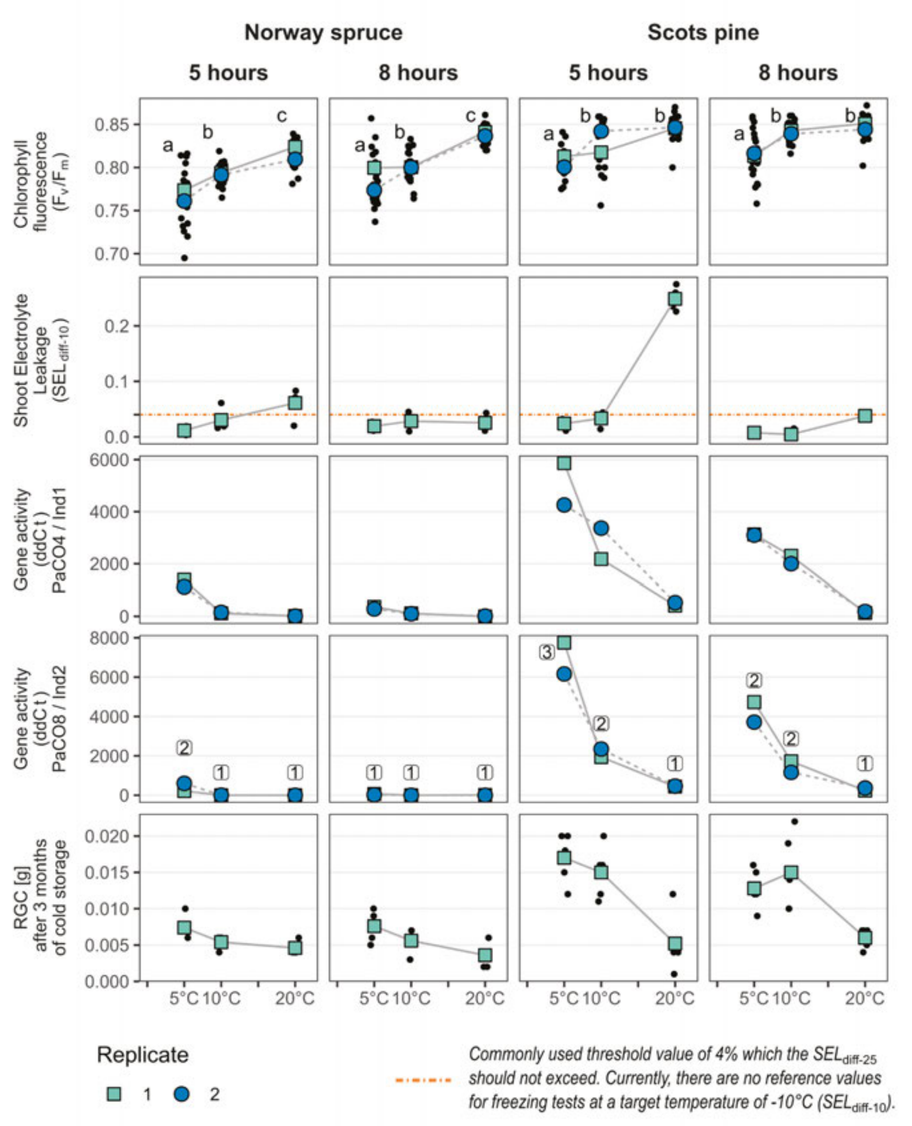



Figure 4.5: Trend comparison of the methods used to assess the cold hardiness of Norway spruce and Scots pine seedlings. The smaller dots are the individual data points while larger shapes represent the mean of the replicate. In the case of the $SEL_{diff-10}$ and RGC measurements where the seedlings were pooled and the value is the total mean. Chlorophyll fluorescence treatments sharing a letter within the same species are not significantly different (Tukey-adjusted comparisons, $p < 0.05$). The orange dashed line is the commonly used threshold of 4% which the $SEL_{diff-25}$ should not exceed (there currently no reference for $SEL_{diff-10}$). The numbers in the square labels indicate the cold hardiness phase according to the ColdNSure™ test. (Paper II).

## 4.4 Light shock mitigation treatments

Reducing the differences between the indoor and outdoor cultivation conditions at the time of transplanting is critical for a successful acclimatization of forest seedlings [182]. During the period monitored for this study, the outdoor PAR reached levels above 2000 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and the UV radiation surpassed 180 $\mu mol \cdot m^{-2} \cdot s^{-1}$ during some days. A sudden change to this environment could be too drastic and cause photodamage on very young seedlings, especially if they had been solely under LED lamps at PPFD levels more than ten times lower and with practically no UV radiation (see Paper III).

Although untreated seedlings experienced a more significant ($p < 0.01$) drop in $F_v/F_m$, the light shock stress was evident for both species in all treatments even during several days after transplanting (see Figure 4.6).

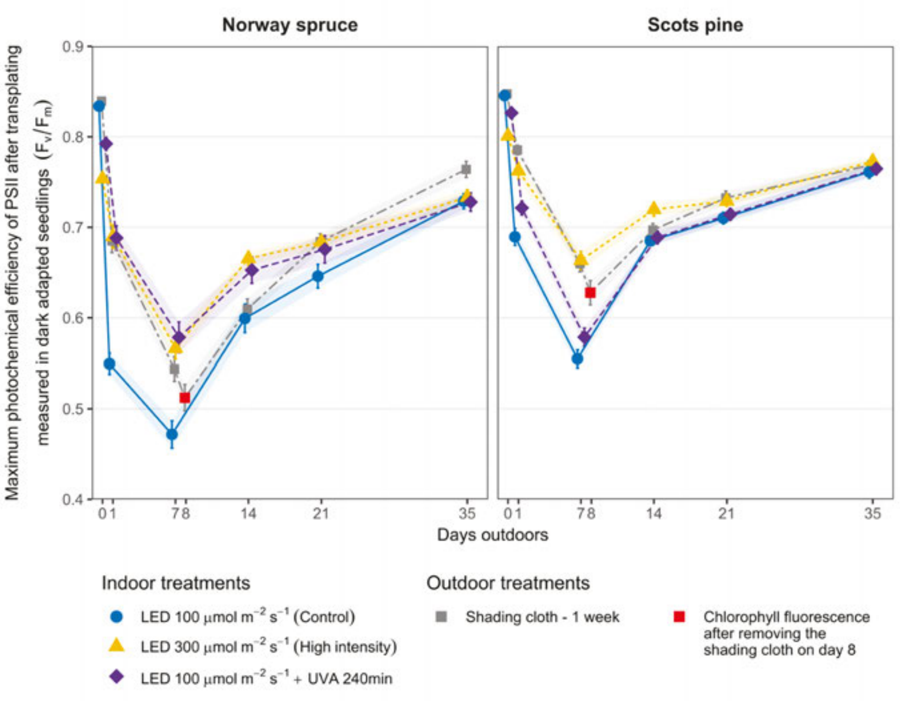



Figure 4.6: Chlorophyll fluorescence (Fv/Fm) after transplanting outdoors for seedlings of Norway spruce and Scots pine cultivated indoors under LED lights. The same individual seedlings were repeatedly measured during the first 35 days of natural light exposure. An additional measurement was performed to measure the effect of removing the shading cloth on the 8th day (red square). The data points represent the treatment sample mean (n = 15 seedlings) at the specific measuring time while the error bars and shaded regions show the standard error (see Paper III).

The slighter reduction in $F_v/F_m$ for seedlings treated indoors (high intensity or UVA for 240 min) suggest that the natural protection mechanisms had started to develop. At first, the shading cloth seemed to have a similar effect, however after it was removed the ChlF levels dropped to those of the control seedlings. This could indicate that the duration of the transient phase was not long enough to allow the seedlings to properly adapt[200].

The results from the ChlF measurements as well as the net $CO_2$ assimilation rates (see Figures 4.6 and 4.7) show signs of an initial light shock stress after transplanting, followed by an adaptation process. After five weeks, the seedlings had produced needles which were adapted to the outdoor conditions.

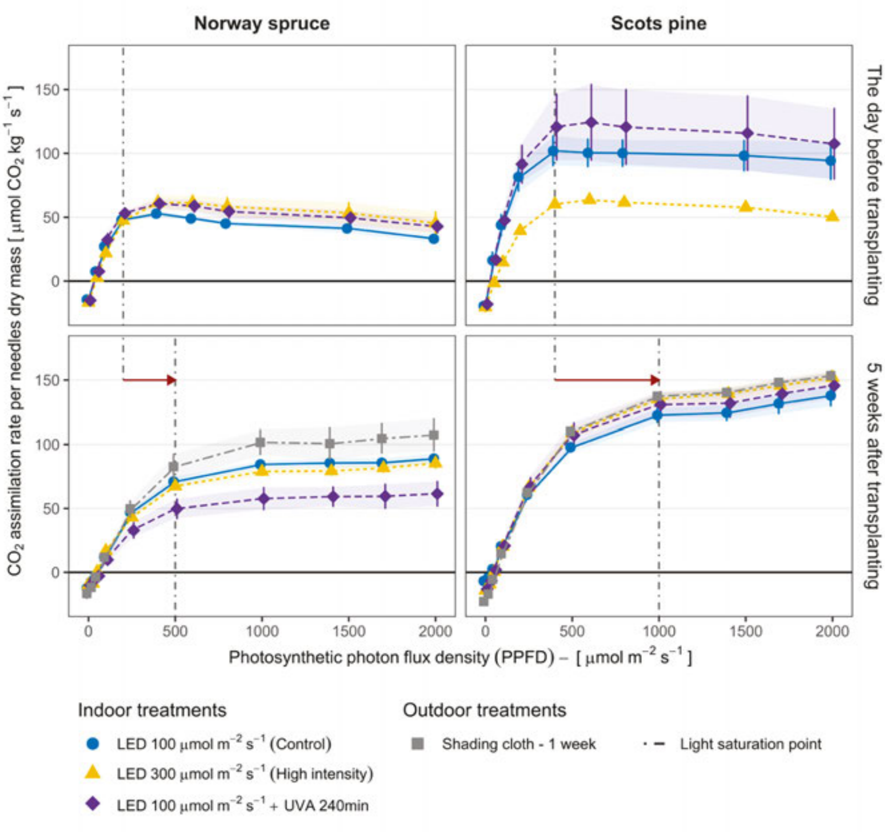



Figure 4.7: Average light-response curves for seedlings of Norway spruce and Scots pine pre-cultivated indoors under LED lights. The net $CO_2$ assimilation was calculated relative to seedling's needles dry mass as a function of the light intensity; measured at a reference $CO_2$ concentration in air of 390 µmol mol$^{-1}$ and 60% relative humidity. The vertical dashed lines shows the shift in the light saturation point. The error bars and shaded region show the standard error of the sample mean (n = 3) (see Paper III).

While photodamage and possible photoinhibition of the PSII could be detected using the $F_v/F_m$ levels [188]; gas exchange measurements allowed a holistic assessment on the effects of transplanting on the photosynthetic process [261, 323]. The net $CO_2$ assimilation rates also changed between the measurement times due to an adjustment process to the outdoor conditions.

Initially, the seedlings had developed their photosynthetic system adapted to the light conditions provided by the LED lamps indoors. As a consequence, the maximum $CO_2$ assimilation was reached at relatively low light intensities. Following some time outdoors under direct sunlight, the seedlings formed new structures adapted to this new environment. As a result, the shape of the light-response curves for both species changed with an evident shift in the light saturation point towards higher PPFD levels.

Being a shade-tolerant species [306], Norway spruce had an initial maximum $CO_2$ assimilation rate at a PPFD of around 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ when measured indoors, regardless of treatment. After 35 days outside, the light saturation point was closer to 500 $\mu mol \cdot m^{-2} \cdot s^{-1}$. For Scots pine, the initial maximum $CO_2$ assimilation rate after the indoor pre-cultivation phase was approximately 400 $\mu mol \cdot m^{-2} \cdot s^{-1}$. However, being a shade-intolerant species [307], the seedlings adapted to the outdoor conditions and after five weeks reached a maximum $CO_2$ uptake at about 1000 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (see Figure 4.7).

At the end of the vegetation periods there were no noticeable difference in the morphological attributes between the treated and the control seedlings in any of the sowings for either of the species. Even though all seedlings were able to withstand and recover from the light shock stress, the fact that they were all affected makes it difficult to predict their full growth potential had the light shock stress been avoided. (Figure 4.8 and Paper III).

Mitigating transplant stress and reducing the risk of light shock is of crucial importance for the success of a year-round cultivation concept using LED lamps. Growth protocols that allow the seedlings to bridge the transition to sunlight exposure with less stress are required. Although indoor treatments that can be directly applied in the growth room facilities would be preferable to avoid additional equipment and extra operations like transport of the seedlings; a transient phase outdoors, under a shade cloth or alternatively below a APV system, could also be beneficial.

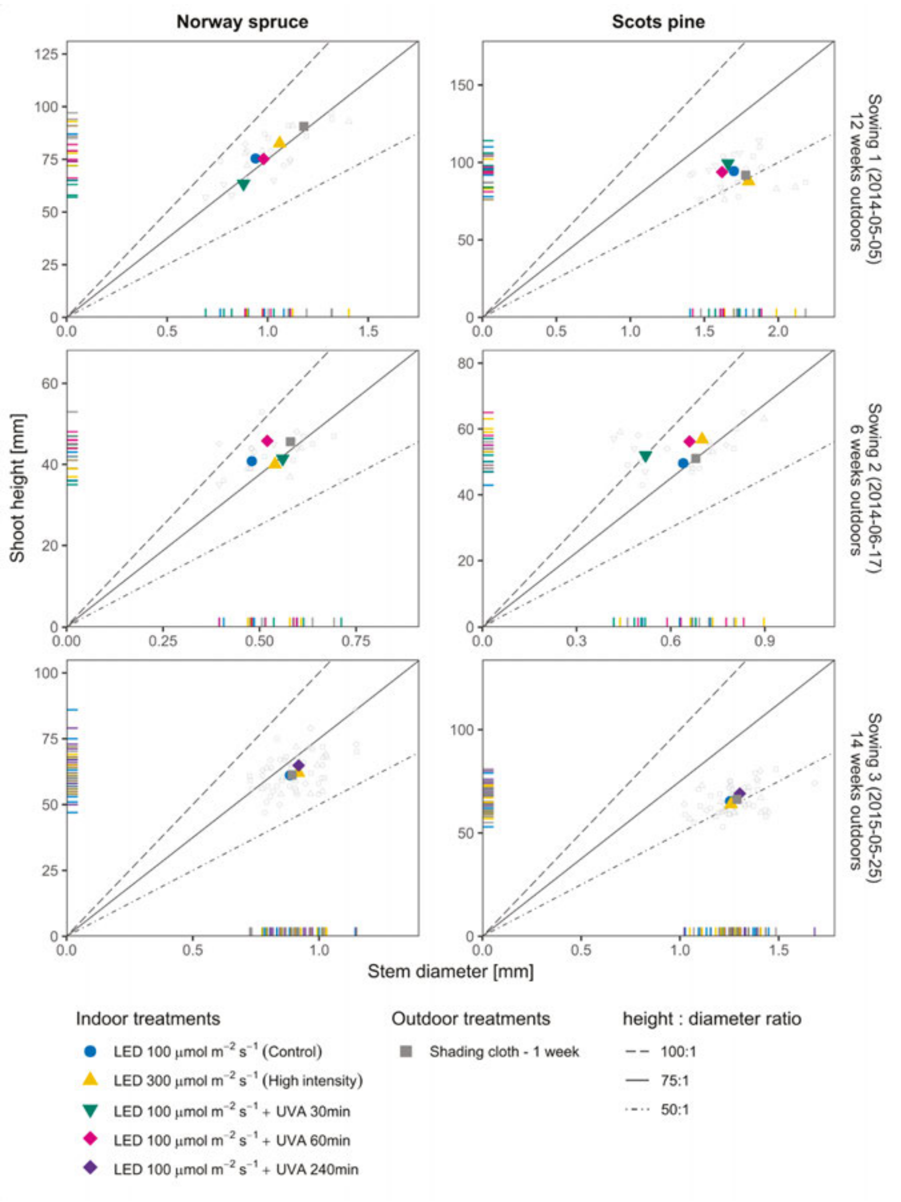



Figure 4.8: Seedling sturdiness as function of the height:diameter ratio for seedlings of Norway Spruce and Scots pine after one vegetation period outdoors at the nursery. Each panel row shows the measurements for one individual sowing with coloured shapes representing the mean of each treatment while smaller points and data rugs show the individual seedling measurements. The diagonal lines indicate the different height:diameter sturdiness ratios (100:1, 75:1, 50:1). No significant differences were found between the treatments at the end of each vegetation period (see Paper III).

## 4.5 Sole-source and supplementary lighting

The growth protocols, particularly the light quantity as a combination of PPFD and photoperiod, can have a significant impact on the electricity consumption when using sole-source lighting. The year-round cultivation concept under LEDs presented in these studies could be scaled up to a vertical multi-layered growth room facility with a cultivation surface of 575 $m^2$. If high density mini-plug containers at 3500 seedlings per $m^2$ were used, production capacity of such a facility would be 2 million seedlings per batch.

Each batch would require at least five weeks of pre-cultivation (Paper I). Moreover, those seedlings produced outside the transplanting window of the vegetation period would also need cold storage; this would add five more weeks for SD-treatments (Paper II). In an ideal scenario without counting downtime and maintenance, four “summer” batches of five weeks each as well as three “winter” batches of ten weeks each could be produced per year.

Using the same pre-cultivation protocol as introduced in Paper I, with a DLI of 5.8 $mol \cdot m^{-2} \cdot d^{-1}$ (PPFD of 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and 16 $h \cdot d^{-1}$ photoperiod), and using adjustable LED lamps (e.g., LED 3) with an average PPE of 8.7 $mol \cdot kWh^{-1}$ (2.4 $\mu mol \cdot J^{-1}$); the minimum daily electricity consumption for lighting for the entire facility would be 383 $kWh \cdot d^{-1}$. This is equivalent to 13.4 MWh for the pre-cultivation cycle (35 days) and 6.7 Wh per seedling.

For those batches requiring cold storage, the energy for lighting during the SD-treatment would be 192 $kWh \cdot d^{-1}$ (same PPFD but only 8 $h \cdot d^{-1}$ photoperiod). This amounts to additional 6.7 MWh per batch for the entire facility or 3.4 Wh more per seedling.

The energy demand for lighting in the growth room facility would be 114 MWh for a year-round cultivation, (94 MWh for the pre-cultivation of seven batches and 20 MWh for the SD-treatments of three batches).With a total expected yearly production of 14 million seedlings, the average energy for lighting would be close to 8.14 Wh per seedling.

In real operating conditions, not all the emitted PAR reaches the canopy and the lamps operate at lower efficacies. To compensate for this, more fixtures are usually installed in the growth room facilities in order to guarantee a homogeneous light distribution at the desired PPFD[175, 201]. All this can result in energy costs that are 50-70% higher: with 10-12 Wh only for the pre-cultivation period and between 12-14 Wh per average seedling.

Adjusting the light intensity in a closed growth facility is relatively easy with dimmable LED lamps[170]. Since the PAR output of LED lamps behaves linearly against the power input, calculating the energy need becomes also simple, e.g., increasing the PPFD to 300 $\mu mol \cdot m^{-2} \cdot s^{-1}$would result in a threefold increase of the electricity demand for lighting (see Paper IV).


Figure 4.9: Average daily supplementary lighting requirements ($DLI_{lamps}$, mol·m$^{-2}$·d$^{-1}$) comparing two control protocols: On-off vs. Adaptive. Three different greenhouse hemispherical transmittances $\tau_{h,\,PAR}$: 40%, 55% or 70%) were assessed assuming a 16 h·d$^{-1}$ photoperiod and a minimum $PPFD_{threshold}$ of 300 µmol·m$^{-2}$·s$^{-1}$ (see Paper IV).

If instead conventional fluorescent lamps were used (PPE of 3.1 mol·kWh$^{-1}$ including the ballast), for an ideal scenario where all light reaches the canopy, the electricity needs for lighting would reach 37.7 MWh for each pre-cultivation cycle at 18.8 Wh per seedling. Furthermore, adjusting the light intensity would not be so straight forward, requiring to add or remove luminaires or to modify the distance from the lamps to the seedlings.

The basic techno-economical advantage of LED lamps compared to fluorescent can be shown with the previous example. However, a more comprehensive assessment should also consider the acquisition and replacement costs as well as lifetime of the luminaires [35].

In addition to fully enclosed growth rooms, the proposed year-round cultivation concept in this work also studied the possibilities of using LED lamps as supplementary sources for photosynthetic and photoperiodic light in greenhouses. The parametric analysis in Paper IV over the spring and autumn months showed a large variation depending on the boundary conditions. Comparing only the control protocols while maintaining all other variables constant (PPFD, photoperiod and $\tau_{h,\,PAR}$); the average requirements for supplementary lighting were always lower when using the adaptive control protocol. This result is similar to what other studies have found [168, 169].

The main reason is that a basic on-off protocol considers the lamps active at full intensity whenever the desired PPFD level is not attained by the transmitted sunlight. With a lower $\tau_{h,\,PAR}$ and higher required $PPFD_{threshold}$ this condition happens more often. On the other hand, an adaptive control is able to take advantage of the available natural light inside the greenhouse, even if it is only in low amounts. Thus, the lamps can provide only the difference necessary to reach the $PPFD_{threshold}$ without needless waste(see Figure 4.9).

For the assumed greenhouse cultivation period of 181 days, the average daily electricity needed to maintain a $PPFD_{threshold}$ of 300 μmol·m$^{-2}$·s$^{-1}$ greatly varied between 0.6 – 2.6 kWh·m$^{-2}$·d$^{-1}$ depending on the conditions (see Figure 4.10). Considering two batches (spring and autumn) using a regular container volume with a density of 575 seedlings per m$^{2}$, the calculated energy for lighting would range between 100 - 440 Wh per seedling for those three months in the greenhouse.

In real operations, it is normally the temperature and not the light which acts as limiting factor during greenhouse cultivation. Lamps are mainly used as sources for photoperiodic light, resulting in lower energy requirements per seedling. On the other hand, thermal requirements in Swedish nurseries (using normally fossil fuels for heating) have been estimated to be between 400 MJ and 1322 MJ per 1000 seedlings (111 - 367 Wh per seedling); with the main difference being the container density (966 vs. 400 seedlings per m$^{2}$) [324].

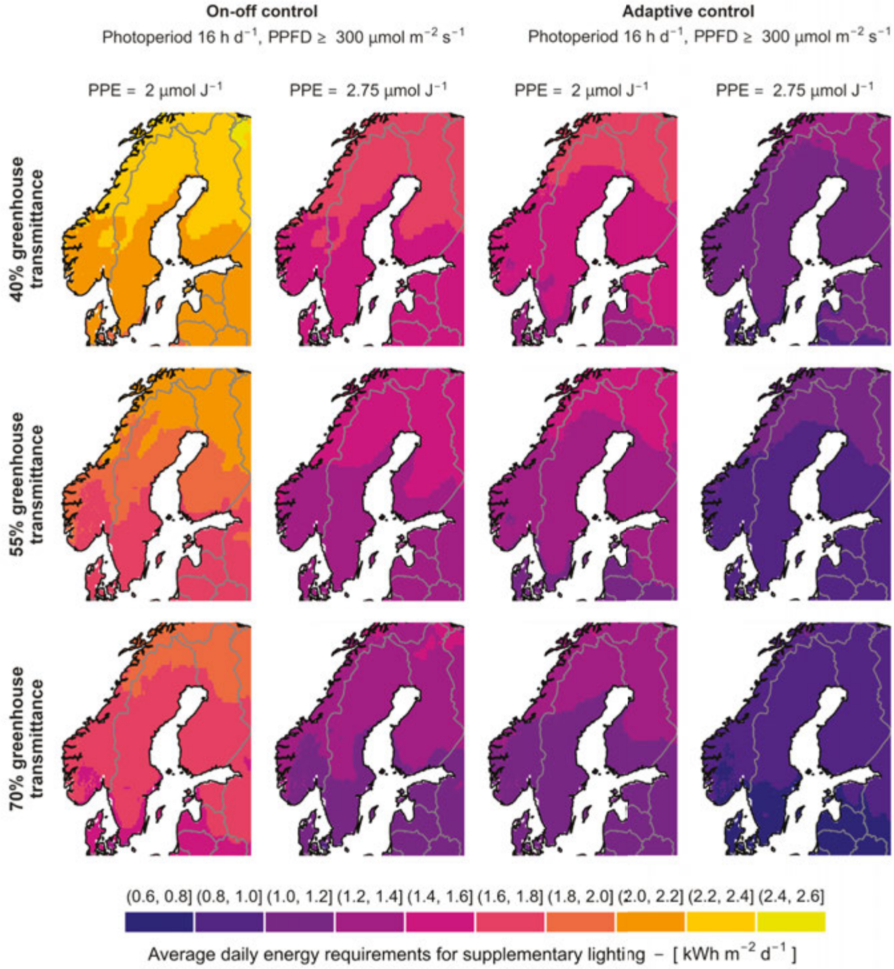



Figure 4.10: Average daily energy requirements for lighting ($E_{el,\ lamps}$, $kWh \cdot m^{-2} \cdot d^{-1}$) for the chosen greenhouse cultivation period of 181 days. Calculated for a photoperiod of 16 $h \cdot d^{-1}$ and a $PPFD_{threshold}$ of 300 $\mu mol \cdot m^{-2} \cdot s^{-1}$, considering two lamp efficacies (PPE of 2 or 2.75 $\mu mol \cdot J^{-1}$) and three $\tau_{h,\ PAR}$ (40%, 55% or 70%) (see Paper IV).

## 4.6 Specific energy yield of PV systems

Even though increasing the seedling density improves the uses of the space and modern LED lamps have considerably better efficacies than conventional light sources [162], using artificial lighting will always come with certain investment and energy costs compared to sunlight [36]. In some cases however, the value of the crop and the benefits of having a fully controlled and standardized environment can justify these costs [172, 175, 201].

Part of the energy costs originated by artificial lighting can be offset by integrating photovoltaic panels throughout the forest nursery area. Together with traditional BAPV and BIPV systems on the roofs of common buildings (e.g., offices, warehouses, carports, etc.), GHIPV systems on the structure of the greenhouses could bring new alternatives where both the quality of the plants and the energy yield can be optimized [209–211, 225, 227].

In GHIPV, the specific energy yield for roof mounted PV systems (25° slope) in this region can range between 400 to 1120 $kWh \cdot kW^{-1} \cdot yr^{-1}$. This considerable variations depends mainly on the latitude, with lower yields in the northernmost regions. For façades (90° slope), a similar range between 400 to 925 $kWh \cdot kW^{-1} \cdot yr^{-1}$ was observed. However, as the azimuth rotated towards an East-West layout, this became less pronounced. (Figure 4.11)

Assuming PV modules with an 18% efficiency, then 1 kW would occupy approximately 5.6 $m^2$. If these modules are installed on the roof of a south-facing greenhouse in mid-Sweden, the energy yield would be close to 170 $kWh \cdot m^{-2} \cdot yr^{-1}$. Based on the calculations of the previous section, a $P_{PV, STC}$ of 120 kW (or 670 $m^2$ of PV) could cover the yearly electric demand for lighting of the indoor growth room facility (114 MWh) (Paper IV).

Finally, instead of using conventional shade cloths, new applications like APV systems in the outdoor cultivation area can provide additional benefits such as: protection against excessive radiation and hail, less heat and higher humidity underneath, and of course electricity generation for the nursery [202, 204]. The design of modules and arrays in APV systems can be optimized to control the PAR transmitted underneath. Transports, machinery movement and other operations can remain undisturbed if the PV modules are installed at sufficient clearance heights above the ground [205, 206]. In the year-round cultivation concept, the seedlings cultivated indoors under LEDs could be transferred to these sheltered APV areas during transient phase to avoid light shock stress from direct sunlight exposure (Paper III).

Even though the method in the study was focused on GHPV, the results of these system estimations can be used for traditional BAPV or BIPV of the same orientation and slope. For free-standing APV systems, the thermal effects of the wind would also need to be considered [220, 325].

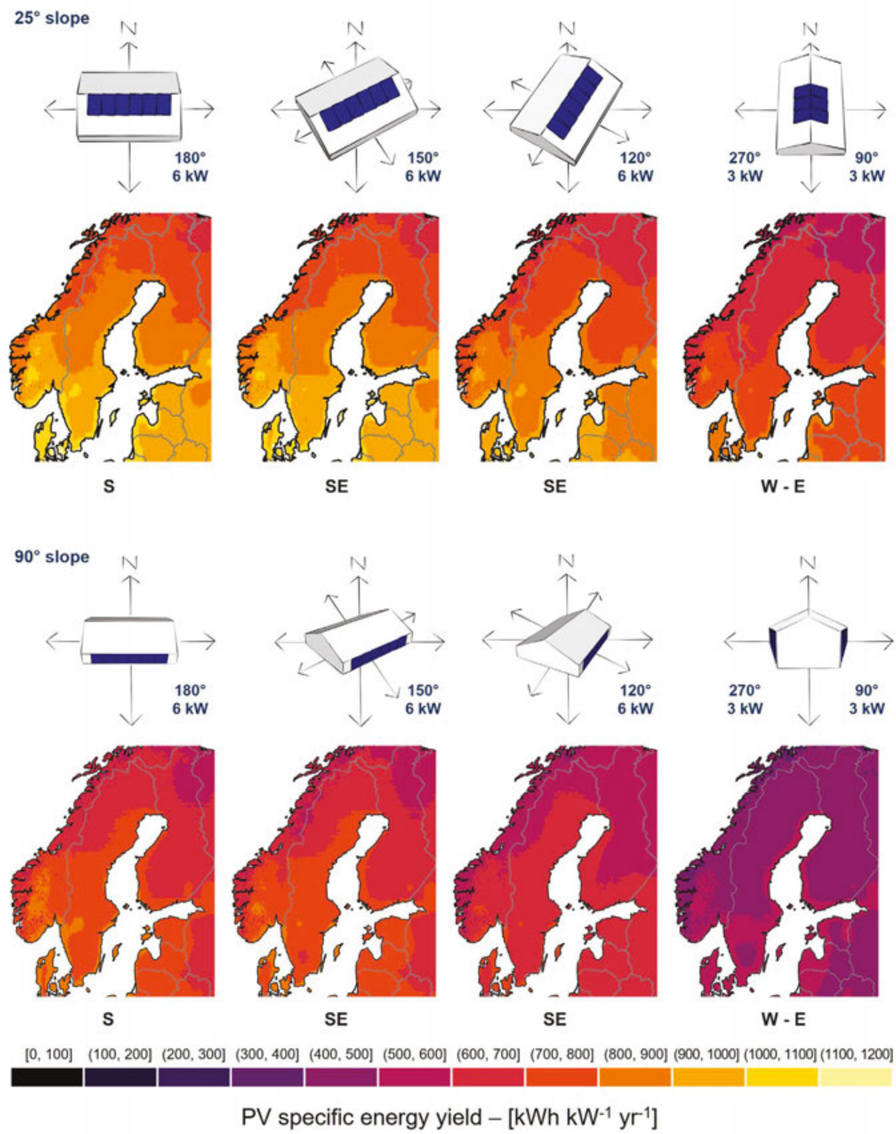



Figure 4.11: Yearly PV specific energy yield ($E_{rel,PV}$, $kWh \cdot kW^{-2} \cdot yr^{-1}$) maps of the Nordic and Baltic countries for PV systems mounted on roofs (25° slope, top row) and wall mounted (90° slope, bottom row) at four different azimuths (South: 180°; South-East: 150°; South-East: 120°; and combined East-West: 90° and 270°). The values were estimated using PVGIS v.5.1 [147] assuming a peak power ($P_{PV,\ STC}$) of 6 kW, c-Si cell technology and estimated system losses of 14%. (see Paper IV for additional estimations distributing the $P_{PV,\ STC}$ between the two roofs directions).

# 5 Conclusions

Light quality during pre-cultivation under LED lamps

- Seedlings pre-cultivated under LED light treatments had equal growth performance compared to those cultivated under fluorescent light, both at the nursery and in the field.
- Considering the other advantages that they have (e.g., adjustable light quality and intensity, more advanced control possibilities, longer lifetime, low radiative heat emissions, and possible reduction in energy demand), LED lamps are a feasible alternative to conventional artificial light sources for seedlings cultivation in forest nurseries.

Light intensity during pre-cultivation under LED lamps

- Suitable PPFD for early cultivation of forest seedlings under LED lights was found to be between 100-200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for Norway spruce and in a range between 200-300 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for Scots pine.
- The electricity consumption is linearly proportional to the light intensity for the LED lamps here studied. Therefore, the light intensity should be optimized to avoid unnecessary energy costs that do not translate in improved seedling quality.

Short-day treatments for cold hardiness induction using LED lamps

- The tested photoperiods (five or eight hours) during the SD-treatment did not show significant effects in inducing cold hardiness in the seedlings of either species when using LED lamps at a PPFD of 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$. However, based on the results here presented, very short photoperiods (under five hours) or too brief treatment durations (under three weeks) are not recommended since enough photosynthetic light should be provided for the seedling to generate sufficient carbohydrate reserves to survive the cold storage.
- Lower temperatures during the SD-treatment, especially for Scots pine, had a significant effect on inducing cold hardiness. Seedlings that had been SD-treated at 5°C presented the highest relative gene expression for cold hardiness, suffered the lowest shoot tissue damage after freezing, and had the highest capacity to grow new roots after three months of cold storage.

Light shock mitigation for seedlings pre-cultivated under LED lamps

- Both the spectral characteristics as well as the light intensity in the growth room facilities differ considerably from the natural outdoors conditions. Further studies on the topic should focus on finding indoor treatments that adjust gradually the light intensity and spectrum including UV-light to levels that are closer to the outdoor conditions.
- The chlorophyll fluorescence levels after transplanting and exposure to sunlight revealed noticeable signs of light shock stress and damage of the PSII on the top needles of all seedlings. However, during the first days there were signs that some preconditioning had taken place. The most affected seedlings were those in the control group for both species but especially for Norway spruce. Having this preconditioning could be valuable, particularly when other stress factors are present.
- The photosynthetic light-response curves revealed sings of acclimation to outdoor conditions for seedlings of both species after 35 days. This in the form of a shift in the light saturation points towards higher light intensities.
- At the end of the vegetation period, seedlings from all treatments were able to withstand and recover from the transplant stress. However, it is difficult to predict the full effect of the light shock stress since seedlings of all treatments were affected.

LED lighting in a year-round cultivation concept

- During the winter months, indoor cultivation in closed growth rooms presents a feasible alternative offering standardized and controlled environment independent from outdoor conditions. The amount of electricity needed for lighting can be optimized by adjusting the light intensity, duration of the photoperiod and using high efficacy LED lamps.
- During the greenhouse cultivation period, LED lamps that allow an adaptive lighting control protocol indicated the highest energy saving potential compared to using an on-off control protocol. This type of control benefits from the available sunlight inside the greenhouse, avoiding unnecessary energy use and supplementing only enough light for the cultivated species.

Greenhouse integrated photovoltaics

- Greenhouses with integrated PV provide an alternative for using the abundant sunshine during the summer and offsetting some of the electricity used for lighting during the darker months.
- In order to avoid negative effects on the plants caused by excessive shading from the solar panels, careful planning is required based on the design, location and orientation of the greenhouse.

# 6 Populärvetenskaplig sammanfattning

Runt 35 % av Europa är täckt av skog, och i de nordiska länderna kan den skogsbeklädda ytan utgöra mer än det dubbla. I Sverige, Finland och Norge är barrskog dominerande, och det finns i genomsnitt 3 ha skog per invånare.

Skogsvård är av lång tradition i norra Europa, och i över 100 år har skogsbrukslagstiftningar funnits för att förhindra skogsförstöring, begränsa avverkningsmängder och kontrollera föryngring efter avverkning. Även om de första skogsvårdslagarna främst fokuserade på att säkra framtida virkesförsörjning har reformer under de senaste decennierna syftat till att balansera ekonomiska, ekologiska och sociala mål. Man har lagt till åtgärder för miljöskydd, och man värnar om biologisk mångfald samt främjar bevarande av natur- och kulturområden.

Bland de många bevarandekrav som införts var obligatorisk anläggning av ny skog efter avverkning en av de första. Detta har idag blivit en nyckelaspekt för ett verkligt hållbart skogsbruk. Skogsägare kan uppfylla denna skyldighet genom att antingen underlätta naturlig föryngring, genom direktsådd eller genom plantering av skogsplantor. Numera är plantering av barrplantor den överlägset mest använda föryngringsmetoden i Norden. För att tillgodose efterfrågan producerar skogsplantskolor i Sverige, Finland och Norge årligen mellan 500 och 600 miljoner plantor. De viktigaste arterna som odlas är gran (*Picea abies* (L.) Karst.) och tall (*Pinus sylvestris* L.).

Den boreala skogsregionen, som dominerar i dessa länder, kännetecknas av korta somrar med måttligt varma och fuktiga dagar, i kontrast till långa och kalla vintrar med mycket begränsat solljus. Dessa säsongsvariationer begränsar vegetationsperioden; den tid då växter kan växa utomhus. Med hjälp av växthus har skogsplantskolorna kunnat odla plantor tidigare på våren och längre in på hösten – och alltså förlänga vegetationsperioden. Dock når även moderna växthus en punkt då de inte klarar av att kompensera för de kalla utomhustemperaturerna och värmebehovet blir för stort. Som konsekvens avbryts odlingen av plantor under årets kallaste månader.

Året-runt-odling av skogsplantor under lysdioder (LED) är en teknik som får ökad uppmärksamhet från plantskolor i de boreala skogsregionerna. Nya odlingsprogram kan erbjuda plantskolor möjligheten att förbättra och standardisera sin produktion samt förlänga odlingsperioden till hela året, oberoende av utomhusförhållanden.

Syftet med denna doktorsavhandling var att ytterligare undersöka implementeringen av LED-lampor i skogsplantskolor. Detta nya koncept inkluderar en förodlingsfas inomhus under LED:s, där plantorna odlas i ett tätt förband i små behållare, följt av omskolning till en större behållare varefter plantorna får fortsätta växa antingen i växthus eller utomhus.

LED-lampor har flera fördelar jämfört med traditionella ljuskällor. De har t.ex. högre verkningsgrad, längre livslängd och mer avancerade styrmöjligheter. För att testa deras användbarhet för plantodling jämfördes tre olika LED-lampor med konventionella lysrör. Biologiska effekter av ljuskvaliteten (vilken bestäms av ljuskällans spektrum, eller färgfördelning) studerades genom att förodla plantor av gran och tall under varje typ av lampa i en odlingskammare med kontrollerade omgivningsförhållanden och sedan jämföra plantornas utveckling och etablering i fält. LED:s visade sig ge lika bra eller bättre resultat än vanliga lysrör.

Effekter av ljusmängd (mätt som ljusintensitet eller energimängd) studerades för båda arterna med det mest lovande LED-spektrumet. För LED-lampor är ljusmängden proportionell mot eltillförseln. Skogsplantorna visade sig dock ha en optimal ljusintensitet vid vilken de växte bäst. Efter denna nivå förbättrade inte ökad ljustillförsel plantornas utveckling, utan kunde till och med orsaka stress. Den optimala nivån var olika för arterna, där gran krävde mindre ljus än tall.

Det nya året-runt-odlingskonceptet gör, som sagt, att skogsplantor kan produceras på vintern utanför vegetationsperioden. Dessa plantor måste dock kyllagras till dess att omskolning kan genomföras på senvåren. Därför måste odlingsprotokoll upprättas för att inducera köldtolerans hos mycket unga plantor. Olika kombinationer av temperaturer och ljuslängder (med hjälp av LED-lampor), så kallade långnattsbehandligar ("short-day treatments" på engelska), jämfördes. Låga temperaturer i kombination med kort fotoperiod inducerade signifikant köldtolerans för tall men var inte lika effektiva för gran.

Till skillnad från vissa trädgårdsväxter som helt kan odlas under LED:s behöver skogsplantor omskolas till friland i mycket ung ålder. Detta utgör en risk för skador på grund av den höga intensiteten i solljuset och den plötsliga exponeringen för UV-strålning som normalt inte förekommer i LED-lampor. Olika ljuschockbehandlingar jämfördes, där plantor antingen exponerades för högre LED-ljusintensitet, UV-strålning inomhus eller en övergångsfas utomhus med täckning av skuggdukar. Initial stresslindring påvisades, men i slutet av experimentet märktes inte längre några behandlingseffekter.

Oavsett hur effektiva LED-lampor blir, kommer inomhusodling alltid att kräva energi. Detta arbete visar att integrering av solcellsmoduler i plantskolor kan hjälpa till att kompensera en del av denna el. Genom att tillämpa adaptiv belysningskontroll kan man dessutom minska onödig elförbrukning. Med rätt optimering kan dessa tekniker fasiliera året-runt-odling under LED:s även i den boreala skogsregionen.

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