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Photovoltaic Energy Production in Greenhouses With Spectral Splitting Solar Trackers

Analysis of the Novel Voltiris System

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Abstract

The spectral filtering low concentration photovoltaic system developed by Voltiris is an innovative solution for energy production in greenhouses without affecting food production. A first prototype was installed in the Swiss greenhouse research center Agroscope in Conthey, Switzerland. During an eight-month agronomic study from March to October 2022, I-V curves were recorded to evaluate the system performance, and the effect of concentration and filtering. The curves showed that the system can achieve a direct normal irradiation efficiency of 10.1 %. The results were benchmarked with those of conventional solar panels placed next to the Voltiris system. The specific power output of the system inside the greenhouse was comparable to the one of a conventional solar panel placed outside. Furthermore, to understand how the filters might affect photosynthesis, the optical properties of the filters were studied and compared to chlorophyll absorption spectra. Spectrometric and radiation analysis showed that the filters reflected 49 % of the incident global radiation and that the spectrum reduced by the reflectance did not impact photosynthesis. To transfer the performance of the system to other greenhouses, the transmittance of the test greenhouse was measured for global and diffuse radiation. The transmission coefficients allowed to separate the effects of the glass transmittance and the greenhouse specific metal structure. In the test greenhouse, the direct transmission coefficient was found to reach a value of 0.28, hence limiting the system yield in indoor conditions to about 28 % of its outdoor value.

Keywords: Trackers, Spectral, Splitting, Photovoltaic, Greenhouse, Innovation

Introduction

Photovoltaic (PV) installations are an important vector to achieve the renewable energy transition and are now to be skilfully integrated into the existing infrastructure. Their deployment on farmland is key to an integration with the potential to reap additional benefits [1]. With more than 7 %, agriculture and transport had the fastest yearly growth rates of renewable energy adoption worldwide in 2022 [2]. However, it is crucial that the energetic production doesn't impact the agricultural yield. Additionally, the lengthy process of permit obtention is a major roadblock for a fast agrivoltaics development in Europe. Greenhouse integrated PV projects are granted faster, as they benefit from an already existing structure. With the greenhouse area in Europe amounting to 150,000 hectares [3], greenhouses could make a significant contribution to the production of PV energy. In the majority of glass greenhouses, light-level-intensive crops (i.e. pepper, tomatoes, cucumbers...), are cultivated, hindering the deployment of conventional PV technologies on the roof of those greenhouses. Optical elements such as gratings and filters have been developed [4-6] to enhance the performance of solar cells and enable their dual use. However, they have not yet been successfully applied to agrivoltaics. The Swiss startup Voltiris developed a spectral filtering PV solution for greenhouses which is studied in this paper. The system is designed to harvest only the light components not needed for photosynthesis. It thus presents an opportunity for greenhouse growers that cultivate light-demanding crops to increase their energetic independence, sustainability and profitability while not suffering agricultural losses. This study shows the impact of the system on the agricultural yield and its energy production potential, with spectrometric analysis, Current-voltage (I-V) curves and specific power output.

Description of the system

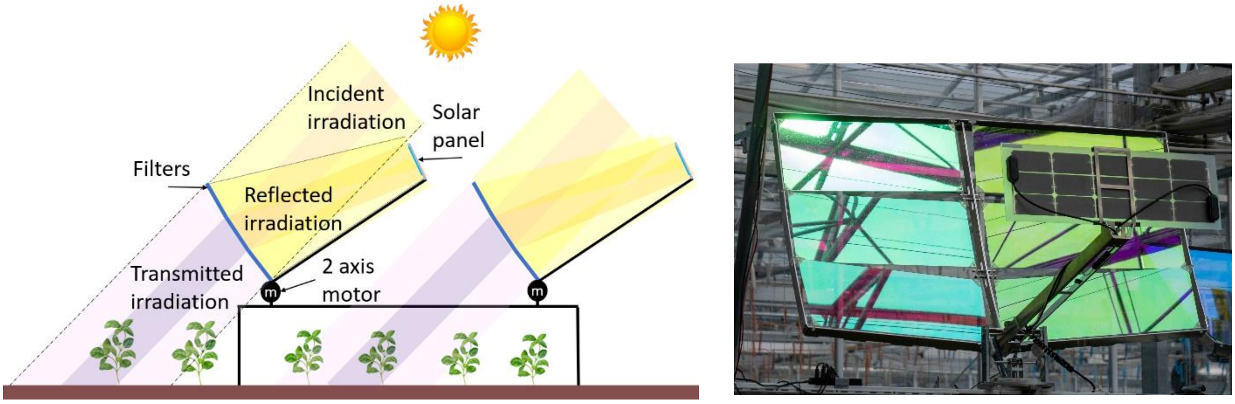

Figure 1: Schematic of the Voltiris system and photograph of the 6-fold concentration (X6) system in the experimental greenhouse.

The Voltiris system is an innovative design using dichroic filters that reflect a part of the spectrum of the incident irradiation towards a solar panel as shown in figure 1. The rest of the spectrum, adjusted to the plants' needs, is transmitted. To compensate for the transmission loss of the filters, the incident irradiation is concentrated on the solar panel. The system is mounted on a 2-axis tracker to further increase PV yield. A first configuration with a concentration factor of 3 (X3 system) on a 30 W solar panel was tested. The following variants were using a concentration factor of 6 (X6 system) on a smaller 25 W solar panel. In the second configuration, a smaller panel was chosen to generate less shadow on the plants. Two different types of dichroic filters, partly reflecting infrared (IR), far-red (FR) and green light were analysed.

Impact on agricultural yield

Table 1: Effect of Voltiris system on yield.

	w/ filter	w/o filter
Tomato		
Cumulative yield	20.75 kg	20.9 kg
Pepper bell		
Cumulative yield	7.89 kg	7.45 kg
Basil		
Fresh weight/m^2	2.49 ± 0.09 kg	2.56 ± 0.10 kg
% dry weight	10.6 ± 0.2 %	10.8 ± 0.2 %

Different plant species (tomato, pepper bell and basil) were tested under the Voltiris system (X3 and X6) with filter type 1 to assess their impact on agricultural yield. Experiments were carried out during the growing season 2022 in two greenhouses and included 2 modalities represented by 2 growing parcels of 6.25 m^2 (2.5 m x 2.5 m). The structure supporting the filters and solar panels was placed above the plants of one modality (called “w/ filter”), the second modality (called “w/o filter”) had a function of control and did not have a filter. For tomato, cultivations under filters have been carried out for 12 weeks and 4 harvests. For pepper bell, cultivations have been carried out during 10 weeks with 3 harvests. The cumulative yield is shown in table 2 for these 2 fruity vegetables. No differences on yield have been observed on tomato and pepper bell whatever the modality (with or without filters). Basil is a leafy vegetable with a short growing cycle (<8 weeks); therefore, 5 full growing cycles were carried out. For the harvest, basil plants were cut at the base, then the fresh matter was weighted and dried in an oven at 100 °C for 24 hours to assess the dry matter. The dry matter was weighted, and the percentage of dry matter calculated. In the same manner, no differences have been observed with or without filters on basil (table 2).

Optical analysis of the filters

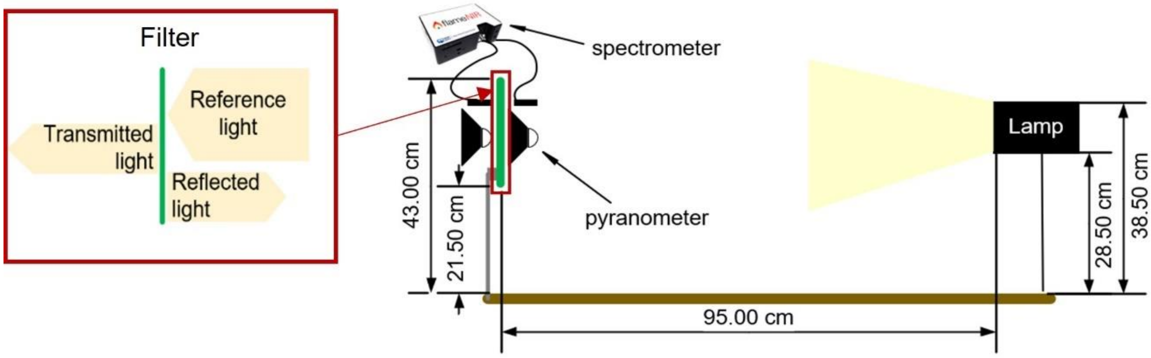

Figure 2: Schematic of spectrometric and irradiance measurements.

In this section, the relative power transmission/reflection, as well as the transmission and reflection spectrum of the filters used for the Voltiris solar modules are shown.

The optical analysis was done inside a laboratory. The schematic of the measurement is displayed in figure 2. Filters were fixed to a mounting system, placed 95 cm from a 1000 W lamp. The spectrum was measured with a Oceaninsight Flame USB spectrometer from 300 nm to 850 nm. The spectra were normalised with the assumption that no losses are created by the filters and that the sum of the transmitted and reflected irradiance is equal to the incident irradiance. The global irradiance was measured with a Kipp&Zonen CMP10 pyranometer in a dark environment, allowing the hypothesis that the only source of light was the lamp. The reference spectrum was recorded at the location of the filter, 95 cm from the lamp. The transmitted and reflected spectra were measured 3 cm behind and 3 cm in front of the filter, respectively.

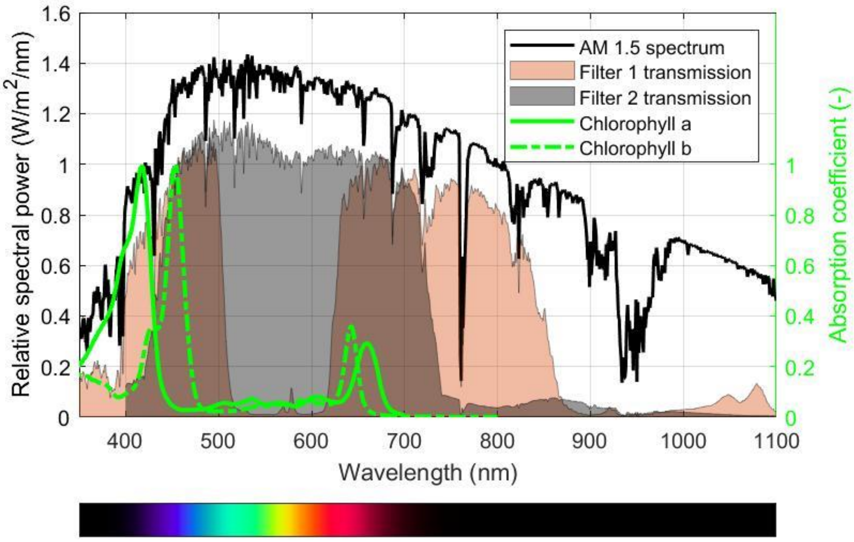

Figure 3: Spectral transmission coefficient of filters type 1 and 2, used for the X3 and X6 systems, compared to chlorophyll a and b absorption coefficients.

Global irradiance measurements with the pyranometer on filter 1 showed that 201 W/m^2 of an incident 395 W/m^2 were transmitted. For an agrivoltaic setting, this translates to 51 % of the incident global radiation being transmitted to the plants, while 49 % being reflected on the solar panel. The spectral transmission coefficient is defined as

$$\text{Spectral transmission coefficient} = \frac{\text{Transmitted light (normalised)}}{\text{Reference light (normalised)}} \tag{1}$$

and the resulting relative spectral power is

$$\text{Relative spectral power} = \text{Spectral transmission coefficient} \cdot \text{AM1.5 spectrum} \tag{2}$$

with the AM1.5 spectrum according to ASTM G173 standard up to 1100 nm, the band gap of silicon. The relative spectral power transmission is displayed in Figure 3 and compared to the absorption coefficients of chlorophyll a and b [7,8]. Filter 1 had the main reflection band between 530 nm and 630 nm and transmitted 47 % of the global irradiance. The low absorption coefficient of chlorophyll in this region indicates that photosynthesis should not be affected by these filters, which was confirmed by no change in yield shown in the previous chapter. The spectrometric analysis shows that a filter with an even wider wavelength range could be used, the cut-on wavelength could be around 500 nm instead of 530 nm. Filter 1 reflected IR and FR irradiance as well, ranging from 850 to 1170 nm. Filter 2 was a near-infrared (NIR) and FR filter that transmitted light in the visible range, allowing a total of 40 % of the global irradiance to pass through.

I-V curves and power analysis

To quantify the performance of the complete system and its efficiency (η), I-V curves were measured for different configurations and compared with the maximum power point (P_{MPP}) of the solar panel.

X3 and X6 systems, a solar tracker and a passive south orientation were tested. Measurements were done outside the greenhouse in Conthey, Switzerland. Voltiris' X3 system was tested 05/07/2022 from 08h45 to 09h30 UTC+2 and their X6 system was tested the 07/11/2022, from 11h45 to 12h15 UTC+1. The irradiance was measured with pyranometers of the Swiss Federal Office for Meteorology and Climatology (MeteoSwiss) and a sun tracker measuring diffuse and direct irradiance normal to the solar panel. Efficiency has been calculated for global normal irradiance (GNI) and direct normal irradiance (DNI) based on this relation:

$$\text{PV efficiency (GNI or DNI)} = \frac{\text{PV power / PV area}}{\text{GNI or DNI}} * 100 \tag{2}$$

$$\text{PV footprint efficiency (GNI or DNI)} = \frac{\text{PV power / System footprint}}{\text{GNI or DNI}} * 100 \tag{3}$$

With a PV area of 0.19 m^2 and 0.16 m^2 for the 30 W panel and the 25 W panel respectively and a system footprint of 3 m^2 for all configurations.

Table 2: I-V curves from X3 and X6 systems.

Graph number	Configuration	PV power	STC P_{MPP} rate	GNI	DNI	η PV (GNI)	η PV (DNI)	η footprint (GNI)	η footprint (DNI)
		[W]	[%]	[W/m²]	[W/m²]	[%]	[%]	[%]	[%]
-	MPP (STC)	**30.0**	100	1000	-	15.9	-	15.9	-
1	X3 system - tracker and filters	39.0	130	815	652	25.3	31.6	1.6	2.0
2	Tracker only	28.6	95	895	725	16.9	20.8	1.1	1.3
3	South oriented (tilted ~30°)	19.6	65	-	-	-	-	-	-
-	1 filter and tracker (calculated: X3 system div. by 3)	13.0	43	815	652	8.4	10.5		
-	MPP (STC)	**25.1**	100	1000	-	15.6	-	15.6	-
4	X6 system - NIR + FR filters	34.2	136	469	353	45.3	60.2	2.4	3.2
-	1 filter and tracker (calculated: X6 system div. by 6)	5.7	23	469	353	7.6	10		

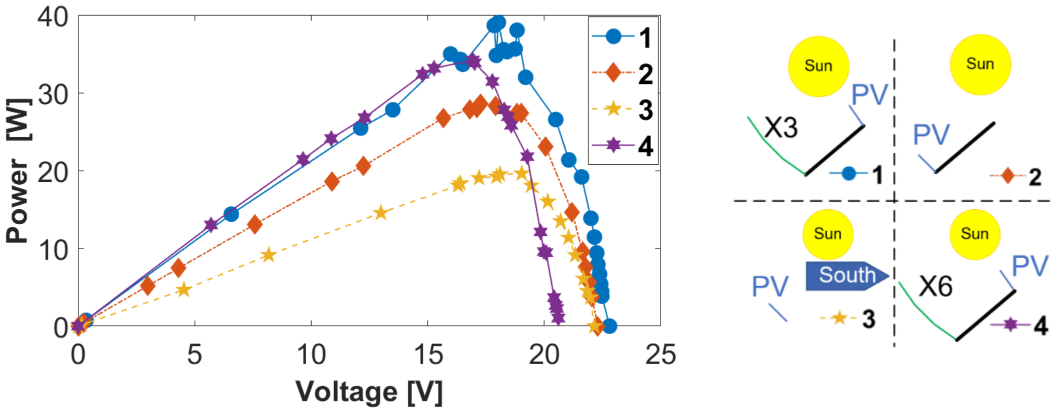

Figure 4: I-V curves from X3 and X6 concentration systems. The legend refers to table 2.

The X6 system was characterised with six filters type 2, only reflecting IR and FR irradiation. Three filters of type 1, reflecting IR and green light were used in the X3 system. The results are displayed in figure 4 and table 2. The X3 system generated 130 % of the PV output, 43 % per filter. This measurement confirmed the observations made in the previous chapter, where 49 % of the light intensity was reflected per filter. For comparison, the same solar panel oriented south at 09h30 UTC+1 generated 65 % of the PV output and 95 % with the sun tracker. The tracker gain is most efficient in the morning evening. The efficiency progress from the X3 to the X6 system is significant, increasing GNI efficiency from 25.3 % to 45.3 % (+80 % increase), both well above the efficiency of the solar panel alone, and the DNI efficiency increased by 90 %. This value is the direct consequence of the two times higher concentration factor. Filters additionally reflecting the green light would further increase the gain of the X6 system. The GNI-based footprint efficiency indicates that the current X6 system could generate 24 W/m^2, on a footprint of 3 m^2 for a 1000 W/m^2 irradiation. Consequently, under these irradiance conditions, 24 W/m^2 could be generated without loss of agricultural yield.

Greenhouse transmission coefficient

Since the Voltiris system is used indoors, the transmission coefficient of the experimental greenhouse was analysed. This enables the performance of the system to be determined independently of local circumstances.

To determine its transmission coefficient, measurements were made inside and outside the greenhouse. The sensors available were photo active radiation (PAR) meters placed inside and outside the greenhouse, a diffuse and direct radiation meter (sun tracker) placed outside the greenhouse and a pyranometer from a nearby weather station (MeteoSwiss). PAR was converted to global irradiation, according to [9], displayed in table 3.

Table 3: Conversion between PAR and GHI based on [9].

μmol/m^{2}s to $\frac{W}{m^2}$ conversion	PAR $[\frac{W}{m^2}]$ = PPFD$[\frac{umol}{m^2 s}]$ / 4.57
PAR to GHI conversion	GHI $[\frac{W}{m^2}]$ = PAR $[\frac{W}{m^2}]$ / 0.442
Gain to correct the measuring device (specific to the device used)	Corrected GHI= GHI*1.1

Comparisons between the outside PAR meter and the MeteoSwiss pyranometer were made and the GHI difference in a one-week period was less than 1 %.

The transmission of each hour for each day of a one-month sample period was calculated following the conversion of table 3. In figure 6 the results are displayed together with the average for a typical day. The integration of the irradiance data indicated that the irradiation inside the greenhouse over the one-month period was 0.55 $\frac{kWh}{m^2 \cdot day}$, and the outside PAR meter indicated 1.96 $\frac{kWh}{m^2 \cdot day}$. The transmission coefficient is thus 0.28. The transmission coefficient for diffuse irradiation was 0.35, calculated on a day with equal diffuse and global irradiation. The steel construction of the experimental greenhouses is denser than that of a conventional greenhouse, resulting in these low transmission coefficients and a significant variance of the transmission coefficient between days (standard deviation between 0.07 and 0.19 for one hour) since the shading of the indoor sensor changes continuously. For comparison, industrial greenhouses tend to have a transmission coefficient of 0.4 in the early morning when the sun is low, and a transmission of about 0.7 at noon [10].

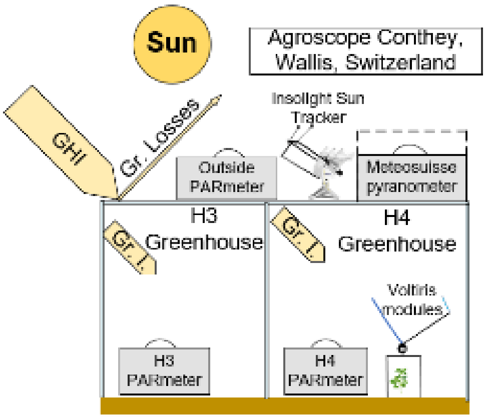

Figure 5: Sensors used for irradiation analysis.

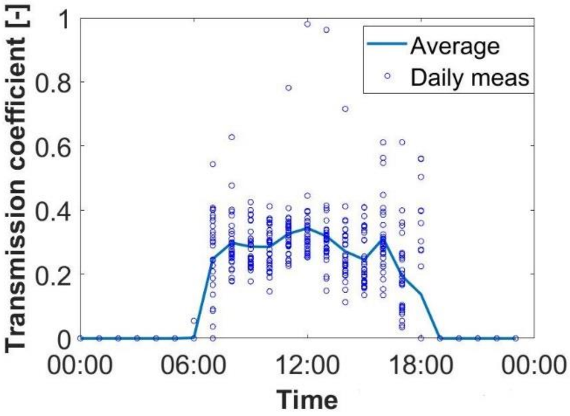

Figure 6: GHI transmission coefficient of the experimental greenhouse, measured daily from 19.10.2022 to 19.11.2022.

Energy production

In this section, measurements of the energetic efficiency of the system are presented.

For two days during February 2023 a comparison was made between the Voltiris system inside the greenhouse and a conventional solar panel of 265 W (16 % announced efficiency) placed on the greenhouse roof, displayed in figure 7. The specific power has been calculated, which is the power production in W/m^2 with the area (m^2) being the area of the solar panel.

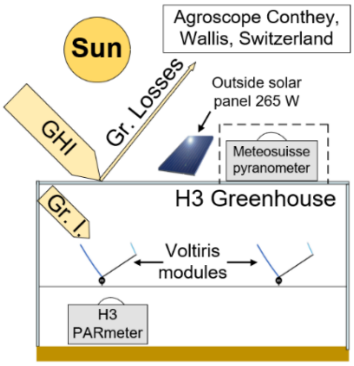

Figure 7: Schematic of the system for the energy evaluation.

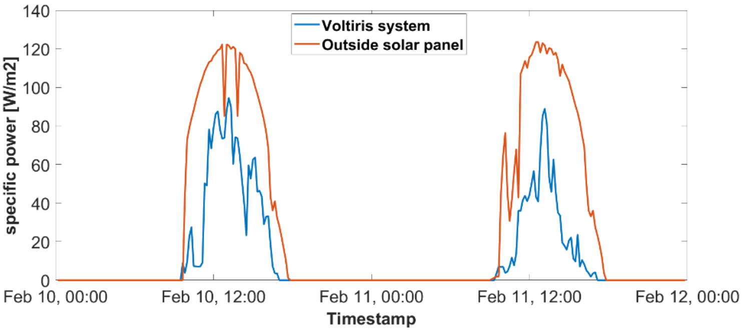

Figure 8: Voltiris system (inside) and standard outside panel specific power.

The specific power is displayed in figure 8. The specific values of the Voltiris system are lower than the ones of a standard panel, due to the shadowing of the experimental greenhouse, shown in the previous chapter. The irradiation losses due to the greenhouse are compensated by the concentration of the light onto the panels.

Conclusion

In conclusion, the spectrometric analysis shows that the green reflecting filters reflect 49 % of the global incident irradiation, while transmitting a spectrum which matches the spectral needs of photosynthesis. No significant impact of the Voltiris system on crop growth could be measured for tomatoes, basil, and pepper bell. I-V curves indicate that the efficiency of the X6 system with filters of only IR and FR reflection could be 45.3 % of the GNI, compared to the 15.6 % measured GNI efficiency of a standard PV module, underlining the boosting effect of the low-concentration PV system. The measured GNI efficiency should further increase with newer versions of Voltiris modules, as the spectrum could be further optimized to be more selective in the transmitted wavelengths, with a cut on at 500 nm instead of 530 nm. For the current system, 2.4 % of the GNI footprint efficiency was measured, without impacting agricultural production. When placed inside of the greenhouse, the Voltiris system presents efficiency losses that are proportional to the greenhouse transmission losses. In this study, performed inside a low transmission greenhouse of 30 % transmission, the Voltiris modules have shown to generate almost as much power per m^2 as a conventional solar panel placed on the outside (per active module area). Better results are expected when placing the system inside of industrial production greenhouses that have far higher (up to 70 %) light transmission than the experimental greenhouse where this study was performed. Furthermore, solar performance can be increased by reducing the transmission range of the filters in the NIR region, as well as by using solar cells with maximum quantum efficiency in the reflected part of the spectrum. While the energy yield of the current system was lower than that of a regular solar installation, the Voltiris system presents a promising alternative to standard greenhouse integrated PV systems, as no agricultural yield reduction has been measured, even for highly light-demanding crops like tomatoes and pepper bell.

Data availability statement

Data are available on request.

Author contributions

Pierre-Vincent Broccard: Investigation, Formal analysis, Visualization, Data curation, Writing- Original draft preparation, Editing. Jonas Roch: Conceptualization, Methodology, Investigation, Resources, Writing- Reviewing and Editing. Daniel Tran: Visualization, Investigation, Writing- Editing, Project administration. Cédric Camps: Conceptualization, Supervision, Resources, Writing- Reviewing. Janina Löffler: Conceptualization, Supervision, Resources, Formal analysis, Writing- Reviewing and Editing.

Competing interests

The authors declare no competing interests.

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