Evaluation of Crops Suitable for Agrivoltaics in Germany – a Review

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INTRODUCTION

Climate change is already impacting agriculture in Germany on large scale. Unusual and extreme weather events such as prolonged droughts, hale, late frost and storms and heavy rain, in descending order, cause on average yield damages of more than half a billion Euro per year (average 1990-2013), and in recent years of more than 2 billion Euro just by drought (2018, 2019), additionally to the effects of heat, hale, storm and sunburn on crop quality. Heat limits photosynthetic capacity, pollination and biomass production. Thus, the limiting factors for crop growth, already presently largely determined by changed growing conditions for plants, will further aggravate in future, and affect overall yield of most crops.

APPROACH

Crops grown in the usual agricultural crop rotation and horticultural crops in Germany were evaluated for their suitability to grow under shading, based on information from literature on their radiation requirements for photosynthesis (PAR) in different growth stages, their morphology and determinants for yield formation, and on agronomic management during the growing season. The results are supplemented by literature data on shading effects and from agroforestry trials. Additionally, the sensitivity of crops to climate change speficially in terms of drought, temperature and radiation (transpiration coefficient; heat, late frost; sunburn) is evaluated, and a comprehensive recommendation for choice of crops in agrivoltaic systems is given, combining and balancing negative influences due to climate change and the possible benefits of shading by AV (Fig. 1).

RESULTS

For categorization of suitability of plants for AV systems various criteria were identified. Important to consider are ***(i) transpiration coefficient, (ii) light saturation point, (iii) maximal netto photosynthesis rate, (iv) temperature optimum, (v) heat threshold, (vi) morphology, (vii) assimilate distribution, storage capacity, yield formation, harvest index.***

The *transpiration coefficient* provides information on the efficiency of crops to use the available water and, thus, on their sensitivity to water scarcity (Table 1). The *light saturation* at which the maximum net photosynthetic rate is reached is between 1,300 and 1,600 µmol/m2s for C3 plants and ≥ 1,600 µmol/m2s for C4 plants. A *PAR* (*photosynthetically active radiation*) of 2,000 µmol/m2s is the reference value for Central Europe around midday in summer (Diepenbrock et al., 2016).

Once the *light saturation point* is reached, even if light intensity continues to increase, the *photosynthetic rate (PR)* of C3 plants is not further increased (Idelberger, 2011), while C4 plants react with increasing PR. For C4 plants *temperature optimum* and *heat threshold* are significantly higher, the *transpiration coefficient* is reduced. PR increases until the *light saturation point*, after which *photoinhibition* starts (Idelberger 2011).

Table 1: Transpiration coefficients of selected crops grown in Germany

Crop	Transpiration coefficient (l H_2O kg^{-1} DM)
Millets	200-300
Maize, beta-beet	300-400
Barley, rye, durum wheat	400-500
Potato, soft wheat, sunflower	500-600
Oats, rape, pea, field bean, red clover	600-700
Lucerne, flax, soy, swede	> 700

Plants have a *heat limit*, but also a CO_2 saturation point. Once these are reached, the PR cannot increase any further or even decreases. Plants with high *leaf area index* (LAI) have higher light use efficiency than those with low LAI. *Yield formation* and *assimilate distribution:* For plants which store assimilates throughout the growing period in storage organs (roots, tubers), a shading effect on yield can easier be compensated. *Harvest Index (HI)*: share of harvested crop in total biomass. Winter wheat: HI 0.55, fodder legumes (as a whole plant) HI 1, rapeseed HI 0.38, sugar beet HI 0.59, potato HI 0.83, oil flax HI 0.40, sunflower HI 0.33, hemp HI 1 (Jacobs, et al., 2018). Raw material, energy crops, fodder crops that are harvested in their entirety: HI1.

The **following ranking** results in relation to

- ***Light requirement***: C4 plants (maize) > C3 plants
- ***Positive effects of shading in dry, hot weather***: celery > potato > wheat > clover grass
- ***Positive effects of shading in wet, cooler weather***: clover grass > celery, potato, wheat
- ***Net photosynthetic rate***: maize > sugar beet > wheat > asparagus or dicots > monocots
- ***Storage capacity (high) of assimilates***: Root and tuber crops > energy/forage crops (legumes, maize) > grain crops (e.g. cereals, rape, flax)
- ***Morphology/ leaf area index (LAI)***: sugar beet, celery, potato > hemp, maize, rape, sunflowers >field bean, grain pea, oil flax, cereals and forage crops with a lower shade tolerance
- ***Assimilate requirements (high)*** in relation to the time available: Grain crops > Energy/forage crops, root and tuber crops.
- ***Harvest index (high)***: Energy/feed crops (maize, hemp, legumes, forage grasses) > potato > sugar beet > wheat > oil flax > rape > sunflower. (Fig. 1)

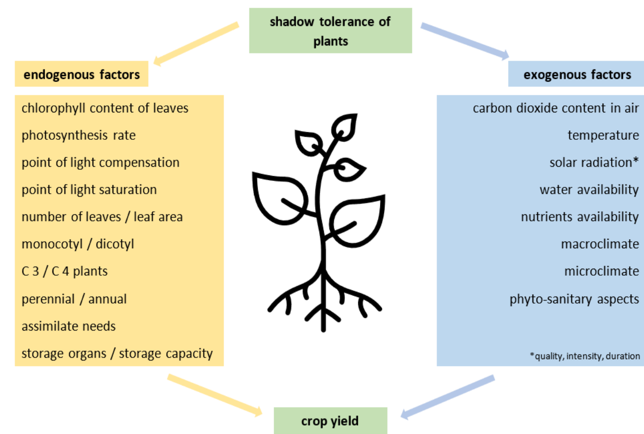

Figure 1: Criteria for shade tolerance of horticultural and agricultural crops

CONCLUSION

Lightly and highly elevated types of AV systems can provide a certain protection of nearly all crops grown in Germany against already existing and future yield losses due to drought, heat and other extreme weather events. Crops that reacted positively/neutrally to shading in previous scientific trials or are known or estimated to be shade-tolerant should be prioritised in particular (Fig. 2). These include agricultural crops such as potatoes, barley, celeriac, and also permanent grassland; furthermore, special crops such as leafy vegetables, cucumbers, raspberries, currants, blueberries, as well as various medicinal plants and herbs appear to be the most suitable for cultivation under AV systems, and apples, pears, elderberries, strawberries and wine to a limited extent. However, if the weather-related yield losses of recent years are considered, a yield gain compared to reference fields without AV can also be expected for: cereals (wheat, rye, triticale), small-grain legumes, hemp, sugar beet, cabbage (few cabbage species), apples, pear, elderberry, sweet/sour cherry, plum, wine, hops, lemon balm, peppermint. Detailed field observations are needed for optimized governance of plant and energy yield, but should not be reason for delay of implementing AV systems which are urgently needed for climate mitigation.

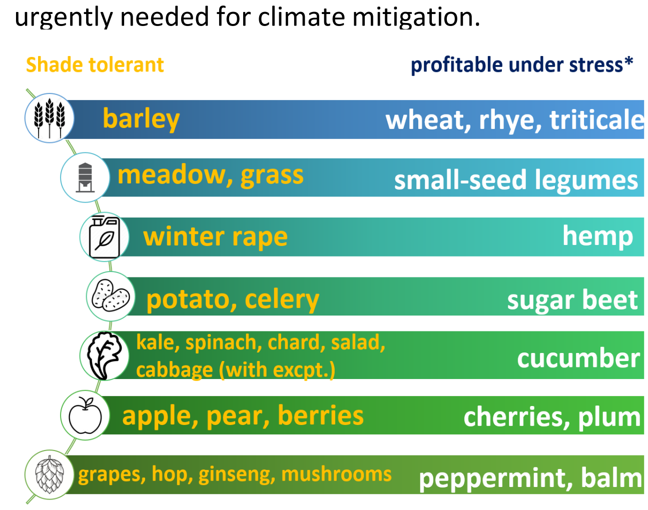

Figure 2: Criteria for shade tolerance of horticultural and agricultural crops

Sources and more information on https://solarinput.de/wp-content/uploads/2022/05/APV-Studie_19052022_Final.pdf