SILPHIUM PERFOLIATUM – A NEWCOMER FOR AN ECOLOGICALLY SUSTAINABLE ENERGY AGRICULTURE

Melina Reckermann, Isabell Seibel
(both in 11th grade, Immanuel-Kant-Gymnasium Tuttlingen and Student Research Center Tuttlingen)
# Table of contents

TABLE OF CONTENTS ....................................................................................................................................... 1

LIST OF FIGURES ........................................................................................................................................ 2

ABSTRACT ..................................................................................................................................................... 2

1. INTRODUCTION ....................................................................................................................................... 2

2. THEORETICAL BACKGROUND ................................................................................................................ 4

2.1. SILPHIUM PERFOLIATUM ..................................................................................................................... 4

2.1.1. BIOLOGY OF THE PLANT AND ITS ECOLOGICAL POTENTIAL ..................................................... 4

2.1.2. AGRICULTURAL POTENTIAL OF THE CUP PLANT ...................................................................... 5

2.2. CORN .................................................................................................................................................... 5

2.2.1. BIOLOGY OF THE PLANT ................................................................................................................ 5

2.2.2. AGRICULTURAL POTENTIAL OF CORN ....................................................................................... 6

2.3. WATER, SOIL AND ECOSYSTEM HEALTH ......................................................................................... 6

3. MATERIAL AND METHODS ...................................................................................................................... 7

3.1. THE TEST SITES .................................................................................................................................. 7

3.2. CONSTRUCTION OF TRIAL BOXES FOR EXTENDED LABORATORY TRIALS .................................... 9

3.3. SOIL ANALYSES .................................................................................................................................... 10

3.3.1. SOIL SAMPLING ............................................................................................................................... 10

3.3.2. ANALYSIS OF THE SOIL SAMPLES FOR HUMUS CONTENT ....................................................... 10

3.3.3. ANALYSIS OF THE SOIL SAMPLES FOR NITRATE ....................................................................... 11

3.4. DETERMINATION OF HUMIDITY, ELECTRICAL CONDUCTIVITY AND TEMPERATURE .................... 11

4. RESULTS AND DISCUSSION ...................................................................................................................... 12

4.1. RESULTS OF THE SOIL ANALYSIS ..................................................................................................... 12

4.1.1 RESULTS OF THE SOIL ANALYSIS OF THE TRIAL FIELDS ............................................................... 12

4.1.2. RESULTS OF THE SELF-MADE HUMUS ANALYSIS OF ALL FIELDS ............................................ 13

4.2. RESULTS OF THE MEASURED HUMIDITY IN ALL FIELDS ................................................................. 13

4.3. RESULTS OF THE MEASURED HUMIDITY IN THE EXPERIMENTAL BOXES ........................................ 15

4.4. RESULTS OF THE NITRATE MEASUREMENTS ................................................................................. 18

4.5. COMPARISON OF THE PHOTOSYNTHETICALLY ACTIVE LEAF AREAS ................................................ 19

5. CONCLUSION .......................................................................................................................................... 19

6. PUBLIC OUTREACH AND EDUCATION ................................................................................................... 21

7. OUTLOOK ............................................................................................................................................... 21

8. BIBLIOGRAPHY ....................................................................................................................................... 22
List of figures
Figure 1: A Melina Reckermann and Isabell Seibel in front of a flowering cup plant in Summer 2020; B water storing cups; C conrated roots of the cup plant; D bees collecting pollen...........................................................................................................4
Figure 2: A sample drawing at the cornfield in Ostrach; B cornfield in Frittlingen; C field in Setingen after weeding..................5
Figure 3: A position of the test field in Setingen in front of the purification plant (red marked area); B – H sequence of experimentation steps.............................................................................................................8
Figure 4: A – E Building of the experimentation boxes; F cup plant in the experimentation boxes.................................10
Figure 5: A distribution of the soil sample in a cup plant field; B sampling of soil samples with the Pürchauer; C incineration of the soil samples ........................................................................................................................................11
Figure 6: A - B preparation of the soil samples; C identification of nitrate in the laboratory and our cellar...............................11
Figure 7: A digging a hole for the sensor; B measurement of the soil humidity; C data reading with the UMP-1 BT application....12
Figure 8: Results of the measured humidity in cup plant and crop fields in Frittlingen. On the horizontal axis you can see the date on the vertical axis the humidity in %. The coloured dots represent the different depths. ......................................................................................................................14
Figure 9: Results of the humidity measures in the boxes (arithmetic mean) from august – december; horizontal axis: time vertical axis: humidity[%] ........................................................................................................................................15
Figure 10: Results of the two first heavy rain experiments; horizontal axis: time after the heavy rain; vertical axis: Arithmetic mean of the humidity in soli in %. Reference (continuous line); Silphie (dotted line); Mais (dashed line). ..........................................................17
Figure 11: Results of the two last heavy rain experiments; horizontal axis: time after the heavy rain; vertical axis: Arithmetic mean of the humidity in soli in %. Reference (continuous line); Silphie (dotted line); Mais (dashed line)........................................................................18

Abstract
The importance of soils for the environment and for humans is often underestimated. Soils are an integral component of nutrient and water cycles and ultimately constitute our basis of life. In our project, we have comparatively analyzed the two energy crops corn (Zea mays) and cup plant (Silphium perfoliatum), an agricultural newcomer, with regard to water retention, nitrate filtration capacity, influence on humus formation and potential for reintegration of depleted soils. The results of numerous laboratory and field trials show that cultivation of the cup plant guarantees a better hydrologic balance, and therefore better nitrate retention of agricultural soils. Moreover, it promotes humification and successful establishment on poor soils is possible. The cultivation of the cup plant can therefore be recommended especially in the context of climate change and in areas where erosion is prominent and water protection is needed.

1. Introduction
Degrading soil health, biodiversity loss, CO₂-certificates for farmers and overfertilization are widely debated and ecological farming methods are needed more than ever before, especially when growing bulk crops, such as energy crops for the production of biogas. Therefore, this project scientifically examines the influence of the cultivation of two very different energy crops, corn and cup plant, on soil health. The interest in this topic arose because biogas is usually described as an eco-friendly way to generate energy. However, in Germany 50% of biogas is produced by anaerobic digestion of energy crops and therefore requires massive cultivation of them. Their cultivation and conversion into electricity, thermal energy, fuels and fertilizers is currently economically incentivized to farmers. The high energy content of corn has led to its increased use for biogas production. This, in turn, entailed a massive corn cultivation in many regions. Corn cultivation has numerous negative consequences for the environment and is potentially endangering soil health. As a wind-pollinated
plant, corn is not supporting pollinators, and because of the late time point of sowing, slow growth, wide row distance and therefore late occurring protective soil coverage, erosion and leakage of soil into water bodies is promoted when cultivating corn. The cup plant, may represent a more environmentally-friendly alternative as energy crop, but is so far understudied.

The importance of soils for the environment and for humans is often underestimated. Healthy soils serve as nutrient, carbon and water storage, water filter, as well as macro- and microorganismal habitat. The sub-ecosystem soil is closely connected with the hydrosphere. Healthy soils can retain large amounts of water inside their pores, which makes it available to plants. Plants in turn serve as the feed for other living organisms. Moreover, the high water storage capacity can reduce floodings during heavy rainfalls and thus prevent erosion. A function vital to agriculture in many regions of the world, as periods of draught and floods have become more common as a consequence of climate change. Additionally, the soils’ pores act as a sieve and water running through the soil is purified mechanically. Health soils can also buffer certain pH fluctuations of precipitation due to their chemical composition. Organic contaminants in the infiltrating water can be broken down by bacteria and other microorganisms present in healthy soils. Finally, soils are crucial to the functioning of the terrestrial carbon cycle. They store carbon in organic humic matter over long time periods and thus prevent release into the atmosphere, where gaseous CO₂ accelerates the global warming [1]. Nonetheless, all those functions are in danger of being compromised. Nowadays, many soils are acidificated as a result of uncontrolled fertilization, with substantial consequences for the environment. Soil protection needs to be prioritized in order to secure the health of our soils through human activity, such as energy crop production [3].

The detrimental effects of corn production on soil health have therefore reinforced the search for alternatives. One of them is the cup plant. In Germany, cup plant seeds are distributed mainly by the Metzler und Brodmann GmbH. The company plans to establish the cup plant as energy crop, because it is a blooming permanent crop, with the potential to increase biodiversity and allowing the sustainable, as well as efficient cultivation of soils, while still being able to secure energy supply [4]. Some advantages and disadvantages of the cup plant are already described in current literature, however frequently they lack a validated scientific basis. Mostly, they rely on experience from cultivation or mere observable characteristics of permanent crops [5]. Therefore, this project scientifically examines the potential advantages of cup plant cultivation for soil health compared to corn cultivation.

Since soil health is a very broadly formulated term, it was defined for the project on the basis of four aspects: 1) The reintegration of barren soils into agriculture; 2) the long-term effect on the humus content; 3) overall nutrient content; and 4) nitrate levels in the soil. The study’s focus has been placed on the impact of both plant species on the hydrological balance of the soil, specifically water retention and drought stress. Since cup plant is currently a more cost-intensive alternative than corn, the study also assessed the most advantageous way to establish cup plant, in order to increase applicability and adoption.
The present study aimed to answer the following questions:

1. What long-term impact does cup plant cultivation have on the soil parameters humus and nutrient content, compared to the corn?
2. Are there differences in the water retention capability of the soil when cultivation one or the other, and if so, what are the differences?
3. How much nitrate can each plant species absorb and what is its capacity to prevent nitrogen leakage?
4. To what extent differs the growth of the cup plant when planted as a seedling, sown from seed, or when later being undersown with the green manuring plant alfalfa?
5. What cultivation can be recommended based on the results and in the context of climate change?

2. Theoretical Background
2.1. Silphium perfoliatum
2.1.1. Biology of the plant and its ecological potential
The cup plant belongs to the family of astaraceae (composite plants) and is a C3 plant. It blooms yellow and originates from the temperate latitudes of Northern America whose climate circumstances are comparable to the ones in Germany [4]. Cup plant silage is used as a substrate for biogas production. The methane yield of the cup plant is around 15 – 25% less than that of corn [20]. On most soils, the cup plant thrives optimally and it is also able to outlast longer periods of cold weather without damage because of its frost hardy rhizomes, which make it ideal for the cultivation conditions on the Swabian Alp. The cup plant can grow up to 2,5 m high. Its leaves are conjoined at the base so that rainwater and dew can accumulate in them. Thus, they function as troughs for insects. Because of the high pollen content its blossoms are approached by a wide variety of insects, including honey bees. Cup plant honey is already marketed. As a permanent crop the cup plant stabilizes the soil of fields permanently, prevents erosions and disturbances of the soil, leads to an active soil fauna and thus an ideal aeration of the soil. Moreover, the crop needs less cultivation with heavy agricultural machinery because of its permanence which preserves the soil from compaction.

Figure 1: A Melina Reckermann and Isabell Seibel in front of a flowering cup plant in Summer 2020; B water storing cups; C conated roots of the cup plant; D bees collecting pollen
2.1.2. Agricultural potential of the cup plant

Initially, the establishment of cup plant is more work- and cost-intensive than annual cultivation of corn. It requires a finely crumbled seed bed which has to be free of weeds [5]. The crop can either be entrenched alone if the seeds/seedlings are pretreated or undersown to corn. This improves its economic efficiency [20]. In the first year of growth, the seedlings can be damaged by snails. Also, the competition with weeds has to be low, otherwise the seedlings cannot survive. This could be seen on the field in Seitingen where weeding was necessary. In common agricultural practice, weeds are often removed mechanically. Chemical weed control with approved soil herbicides right after the seeding is also possible. In the second year, weed control is not necessary anymore. The farmer from Frittlingen who supported this project weeds his cup plant fields twice a year mechanically from the second year of vegetation. In contrast to his corn fields, he does not use any herbicides on the cup plant fields. In the first year of growth, cup plants form a leaf rosette which cannot be used for the biogas production. From the second year onward, the cup plant can be harvested every year between mid-August and mid-September. The German fertilization ordinance currently prohibits fertilization of monocultures of cup plant. If cup plant is undersown to corn, the fertilization ordinance can be bypassed and the field may be fertilized. The trial fields in Frittlingen were fertilized with 170kg fermentation residues for 35t cup plant mass annually. In comparison to corn, a mineral fertilizer is not needed. In Germany, cup plant is currently cultivated on approximately 3000 ha [6]. The oldest field of cup plants in Baden-Württemberg has been established in 1981 by the LAZBW Aulendorf and has been continuously harvested annually since then, with no depression of yield [6] or pest infestations [5]. In order to obtain funding from the Greening program (CAP) of the European Union [8], agriculturists have to produce Ecological Focus Areas (EFAs). The cup plant is an ideal crop for EFAs, because it does not require pesticides, prevents denudation and also roots and secures the soil permanently.

2.2. Corn

2.2.1. Biology of the plant

Corn is an annual plant and belongs to the family of poaceae (sweet grass) [9]. It has a 4cm thick and 1 – 2,5m long stem. The long leaves stand in two rows. The roots do not enter the soil as deeply as the cup plants. On the first overground stalk knot, the corn forms stilt roots which stabilize the plant. The corn is monoecious with terminal male panicles and female cobs in the axils. It belongs to the C4-plants and is therefore able to

Figure 2: A sample drawing at the cornfield in Ostrach; B cornfield in Frittlingen; C field in Seitingen after weeding.
use solar energy very efficiently. Warm and well-drained soils are preferred. Neither water logging nor moor soils are tolerated.

2.2.2. Agricultural potential of corn

Corn seeds need a well prepared and consolidated seedbed and must be inserted 4cm deep into the ground where the light and temperature conditions are ideal [10]. The soil temperature has to be at around 8°C at the time of sowing. By dressing the seeds, damage from fungi, crows or fruit flies can be prevented. Drought during sprouting can lead to large crop losses. In the region of Tuttlingen for instance, many farmers were forced to sow a second time during 2020 due to unfavourable draught conditions. In corn fields, it is necessary to control weeds as early as possible because of the low level competitiveness of young corn plants. At first, foliar and residual herbicides are used. If the plant has between five to six leaves, they receive a secondary treatment. If other competitors like cranesbill or different millets occur at a later time they can be treated specifically. In order to combat pests such as wireworms an approval is necessary. The European corn borer can be combated with an insecticide or a deep cut at an early harvest. As a quarantine pest, the corn rootworm has to be reported and afterwards also combated. Therefore, a diversified crop rotation can help [20]. The trial fields in Frittlingen were fertilized with 190 kg that consist of 95% fermentation residues and 5% of mineral fertilizer at a yield of 35t corn. Additionally, herbicides were used annually. In Germany, corn fields make up 20% of the total agricultural land (2.5 Mio ha). Thereof, 80% is silage corn which is used for biogas production and cattle food, while 20% is corn maize [10]. The rising corn cultivation has been criticized for the contribution to soil degradation on the cultivated areas, due to unilateral crop rotation, high risk of erosion, degradation of humus and biodiversity loss. Measures such crop combinations, catch crops or mixed cultivation could render large-scale corn cultivation more environmentally friendly [9].

2.3. Water, soil and ecosystem health

Humus is important for every fertile soil. The term humus describes the amorphous compartment of organic matter in the soil involved in composition, reduction and conversion processes. Humus is also a constant nutrient source for plants and for most soil biota [10/11]. Humus has a good water storage capability and therefore a positive impact on soil water balance. Additionally, humus supports soil biota, which in turn are able to clean soil water from harmful substances before entering ground water [12]. Proteins and humic substances are an important part of humus. They are able to buffer pH variations in soil and soil-borne water, which is important to uphold biochemical processes in the soil [11]. This also leads to a buffering of the soils water. During humus production by soil biota clay-humus complexes are built, which form stable crumbs of soil that help avoiding degradation and silting. Moreover, clay-humus complexes increase the pore volume and thus have a positive impact on soil aeration and water household [12]. Clay minerals themselves also store water, increasing water availability for plants, they support an active soil biota, increase water storage capabilities and water percolation. This helps to prevent soil compaction and makes tillage easier [11].
Climate change causes an increase in extreme weather phenomena, like heavy rainfall and extended periods of draught. Therefore, it is more important than ever before to safeguard the water balance in soils by protecting humous content. The capability of healthy soils to store, clean and release water has a critical impact on ecosystems and on crop survival, thereby safeguarding stable food production, preventing leaching and keeping our ground water clean. But agricultural soils are in danger of wearing out, due to the cultivation of high-nutrient demanding crops, such as grains and root crops.

The soil humidity has a critical impact on the pedogenesis, where overground drain, infiltration and percolation, rising ground water, and relocation inside the soil act as starting points for the underlying processes. Different soil horizons form, depending on parent material, climate, topography, biota and time. Overground drain leads to degradation and erosion, which transport soil particles along geographical decent. The percolation of rainfall causes material to redistribute into deeper horizons, e.g. of soluble salts and carbonates, clay minerals and humus [13]. Therefore, measuring soil humidity can give an indication on the processes taking place in the soil. Other than redistribution, soil fecundity, the water demand of plants and the diffusion of nutritive and harmful substances in deeper layers of the ground water are influenced by soil humidity. In addition, data can be gathered about the intensity and depth of water infiltration and water holding capacity of soils. Altogether these steps can help to get an impression for the interaction of water and soil, and important information about transformation processes in ecological systems can be gained, on the basis of which necessary measures for soil and environmental protection can be concieved.

The soil at the project’s primary measuring site in Frittlingen, is a sandy loam, with a high percentage of coarse pores and a little percentage of medium and fine pores [14].

A controlled fertilization with nitrogen (N) compound leads to a high revenue growth and a higher soil fertility. Farmers can choose between synthetic mineral fertilization, slurry and green manuring. Often, a combination is used [15]. But often fertilization causes N overspill, because the plants cannot use all the N. Consequently, a multutde of complicated environmental and human complications arise. The soil biota transform ammonium into water-soluble nitrate which may leak and contaminate ground water. There, nitrate can be transformed into nitrite which is hazardous to health. When nitrate contaminates surface waters it causes eutrophication and a higher production of plant mass, which can push ecosystems out of balance. Moreover, uncontrolled N fertilization directly and indirectly contributes to climate change, because 1) nitrate can be transformed into the greenhouse gas nitrous oxide and 2) fertilizer production leads to the emission of large amounts of CO₂ [16].

3. Material and methods
3.1. The test sites
The three trial fields have been chosen due to their different conditions. This allows to investagate the potential of corn and the cup plant. The fields of the Metzler Brodmann GmbH in Ostrach which are located directly on a slope were chosen as the fist test site, where cup plant as well as corn have been cultivated for
eight consecutive years. They are comparable to test site 2, the fields in Frittlingen where cup plant has been cultivated for eight consecutive years for a biogas plant. They belong to Mr. Benne who is the owner of the Bihrenberghof and allows to take samples on his fields. Both cup plant fields are located next to corn fields. The field in Seitingen, lies directly adjacent to the water purification plant and provides a rather barren soil. It has been constructed from the excavation masses from the newly built purification plant. The soil barely contains any humus and is not being fertilized. Therefore, this trial field has been used to assess the potential of cup plant to grow under disadvantageous soil conditions and to rebuild a healthy soil structure.

The aim of the trial in Seitingen was to learn how cup plants and corn cope with poor soil conditions, as well as to determine the difference in growth of the cup plant when planted as a seedling, sown from seed and sown from seed with subsequent co-cultivation of green manuring plants. At first, the trial field had to be weeded to simulate the typical starting point on an agricultural field. Weeding was conducted at three additional time points thereafter (08 June, 21 July and 01 September). On 21 May 2020, the field was divided into four different sections which were separated by weed barrier fabric. In the section 1, 178 cup plant seedlings (3 – 7cm tall, in the three-leaf stage) were planted in four rows. Before planting, cup plant seedlings were cultivated at home in humous plant soil. Afterwards, they were watered with nitrate-enriched water from the water purification plant (11mg/l) for several weeks so the seeds could grow optimally. On the 08 June, 29 seedlings had to be replaced due to snail damage. In section 2, cup plant seeds were sown on the 21 May and in section 3 cup plant seeds were sown with consecutive cultivation of alfalfa from seeds. Alfalfa has been chosen as green manuring because it was determined to be the ideal green manuring plant in previous experiments [7]. Within section 4, 150 corn seeds were sown and dressed with chili and beer before to

---

1 The map was provided by the commune of Seitingen.
prevent loss due to crows. Seeds were sown at 4cm depth and 28cm apart [20]. The corn and cup plant seeds were watered *in situ* with the nitrate-enriched water (11mg/l).

In order to be able to compare the three cultivation methods used for cup plant, the phytomass of fully grown-plants was determined by measuring the leaf surfaces of 20 randomly chosen plants per section at the end of the vegetation period. Imaging and automated optical measurements (ImageMeter application, Google Play) of randomly selected leaves was carried out as illustrated in figure 3D. The average surface content was calculated by arithmetic mean. A proportional relation between the leaf surfaces and the phytomass can be assumed within the same plant species. Therefore, this method can reliably determine differences in phytomass between growth conditions without damaging the plants. To guarantee that the soil in Seitingen is as poor as expected, soil samples were analyzed (see 3.3.3 soil samples).

On the two agriculturally used trial fields in Ostrach and Frittlingen, the humidity in different soil layers was measured over half a year, mostly after specific weather events and after harvest. The two selected fields are adjacent and have the same soil type. Thus, assumptions can be made about the influence of deep rooting, multiannual crops compared to shallow rooting, annual crops on soil water retention capacity.

### 3.2. Construction of trial boxes for extended laboratory trials

To investigate the effects of the plants on the soil under defined conditions, seven trial boxes were built complementary to the field trials. In total, two double boxes and two single boxes with the inside measurements 97x97x125cm and an acrylglass viewing window as well as one reference box without a viewing window have been built (Figure 4A-D). To retain the soil in the experimentation space, the boxes have been lined with a perforated plastic foil. The viewing window (Figure 4A) allowed the constant visual monitoring of the development of the rhizome. To prevent exposure of the roots to UV light, the glass has been covered with protective dark fabric. The reference box has been built to demonstrate the behaviour of water in the soil of fallow grounds (Figure 4E). Each box has been filled with 0,5t of humous soil so that water and nitrate levels could be monitored under optimal growing conditions and fallow, respectively. To populate the boxes, cup plants and corn have been replanted from the trial fields in Ostrach into the boxes on 23 June 2020. It was chosen to replant annual corn and established, fully grown cup plants into the experimental boxes, because they were expected to be more representative for cup plant fields in agricultural use (Figure 4F). All plants origin form adjacent fields with identical conditions from the Ostrach site.
On one side of each box four holes on the levels 30, 60, 90 and 120cm were drilled in order to access the soil with the humidity sensor at representative soil depths (Figure 4D) to draw conclusions about the water retention potential at different root zones. To avoid water evaporation and loss of soil matter through the measurement holes, a removeable batten as well as an insect net was placed over each hole. Over a period of 3.5 months, humidity and electrical conductivity were documented daily for each measuring site and box. In parallel, precipitation was recorded daily throughout the experimentation period.

In order to investigate water retention capacity of the roots under defined conditions, heavy rainfall was simulated four times in different stages of vegetation where the humidity of the soil was documented before and after 1 hour (h), 4h and 15h after the simulation. Heavy rainfall was mimicked by watering 40 l/m², which corresponds to an actual heavy rainfall and could be measured in our region several times before. Simulations occurred at four representative stages of vegetation: 1) 88 days after replanting 2) after the cup plant was harvested, 3) after the harvest of corn and 4) after germination of the catch crop alfalfa in the corn boxes.

3.3. Soil analyses

3.3.1. Soil sampling

To assess the initial soil quality and humus content of corn and cup plant fields at the Frittlingen and Seitingen sites at project start, 25 samples were taken across the fields at a depth no deeper than 30cm, which corresponds to the average depth of the humus layer, with the help of a boring rod. The entire sample was collected in the same sample bag and frozen at -20°C immediately. Afterwards the samples were pooled for analysis. Subsequently throughout the experimentation period, nitrate concentration was analyzed in samples collected at one meter into the perimeter of the fields in Frittlingen, Ostrach and Seitingen to continuously monitor the development of the nitrate concentration. Two samples were collected at each field and timepoint. The used boring rod is pushed into the soil with considerable force by hitting it with a rubber mallet and the sample is retrieved by simultaneously rotating and pulling the rod. The samples were put in several sample bags and frozen afterwards.

3.3.2. Analysis of the soil samples for humus content

The initial humus content and nutrient concentration at the Frittlingen site was analysed by a commercial laboratory. But the measured difference of 0,2% on the two fields in Frittlingen is a quite little number taking into account that smaller discrepancies are always possible. To confirm the commercial laboratory’s results with own measures, 15 samples were retrieved from cup plant and corn fields at the Frittlingen and
Seitingen sites and analyzed individually. They were submitted to a similar protocol.\(^2\) After that the quality of the measured data was mathematically proofed.

![Figure 5: A distribution of the soil sample in a cup plant field; B sampling of soil samples with the Pürckhauer; C incineration of the soil samples](image)

### 3.3.3. Analysis of the soil samples for nitrate

The samples were taken with the boring rod from 1m depth (21 from the boxes, 72 from fields in Ostrach, Seitingen and Frittlingen) and were treated according to the log of the “Landwirtschaftliches Technologiezentrum Augustenberg” [18]. After freezing, drying and homogenizing, the samples were weighed exactly and a definite calcium chlorid solution was added. After a definite shaking and a filter process the nitrate concentration could be measured by using the Labquest nitrate electrode from Vernier.\(^3\)

![Figure 6: A - B preparation of the soil samples; C identification of nitrate in the laboratory and our cellar.](image)

### 3.4. Determination of humidity, electrical conductivity and temperature

Volumetric soil humidity, soil temperature and electrical conductivity were measured using a UMP-1 BT sensor (Umwelt-Geräte Technik GmbH UGT) by inserting it’s two 10cm long measuring rods fully into the soil, to acquire correct measurements. Measurements were taken at a total of 10cm and 40cm depth. (Figure 7A-B) Measurement data were digitally recorded via the corresponding phone application UMP1-BT (Figure 7C). As follows: 1) Humidity: 0-100% was volume water content; 2) electrical conductivity as 0,001 - 5mS/cm; and 3) temperature as -20 – 60°C. To analyze the soils’ coping with changing water conditions, measurement at the field trial sites were acquired after either extended periods of drought (e.g. 24.07., 26.07., 01.08.) or heavy rainfall (e.g. 02.-04.08.). This also served as an internal control for the mimicked weather conditions and related results acquired at the trial boxes.

---

\(^2\) The process will be explained in the interviews.

\(^3\) The exact process will also be explained in the interviews.
4. Results and discussion
4.1. Results of the soil analysis
4.1.1 Results of the soil analysis of the trial fields
Due to restrictions regarding the use of chemicals, it was not possible to do a detailed soil analysis in the student laboratory, and the agreed appointment with the soil analysis laboratory (Becker, Leipferdingen) had to be canceled because of the current pandemic. Therefore, the prepared composite soil samples from our two trial fields in Frittlingen, as well as from one field in Seitingen were sent to an alternative soil analysis laboratory (Raiffeisen AG, Euskirchen) where a detailed analysis was made.\textsuperscript{4} Overall, it is striking that the cup plant field as well as the corn field at the Frittlingen site, have an extreme oversupply of many nutrients. This represents a potential threat for surrounding ecosystems due to the risk of leakage into the groundwater. Moreover, the observed oversupply was more pronounced in soil samples gathered from the cup plant field which indicates a lower nutrient requirement of the cup plant compared to corn. Consequently, the cup plant might require less fertilizer and hence the cultivation of cup plant can overall reduce the risk of fertilizer contamination in the ground water compared to corn cultivation. The latter corresponds to similar observations made at the Seitingen site. However, this advantage is only given when the lower nutrient requirement of the cup plant is being considered when fertilizing. Otherwise, the nutrient surplus is exacerbated and might cause the opposite effect.

When measuring N content, the corn field and cup plant field contained 404mg/100g has and 471mg/100g, respectively. The measured overall excess of N availability may render plants less resistant to diseases and may increase the risk of N leakage into the ground water. In agreement with the observations made regarding nitrate levels in the trial boxes, corn likely consumes more N than cup plants.

The average humus content is between 4 – 11.5% in the topsoil at Swabian Alb. The high humus content of the soil of both fields is considered positive. The humus content measured at the cup plant fields is markedly higher than in corn fields, with a humus content of 8.8% and 8.6%, respectively. The 0.2% increase in humus content in cup plant fields can be seen as a tendency of soil recovery due to the extended time periods of undisturbed humification processes, as cup plant is grown multi annually. This finding is of special interest because after the harvest, parts of the corn roots stay in the soil and are allowed to decompose, while cup

\textsuperscript{4} The complete results of the analysis will be brought to the interviews such as their exact influence on plants.
plant is grown multi annually, and the roots remain alive after harvesting. Therefore, the humus content in the corn field should hypothetically be higher. This is not the case, likely because corn plants consume larger amounts of humus during their growth period and therefore reduce stored humus. Additionally, corn cultivation requires more working operations and mechanical interference in their course impede the humification process.

Soil analysis was equivalently carried out at the Seitingen site as a control, and to proof that the soil was barren. An extensive deficiency in all measured nutrients could be observed as well as an overall low humus content (2.5% of total mass). A heavy metal pollution which would have had a similar effect on the growth of the plants could be precluded by analysis. Therefore, the soil had unfavorable growing conditions and could be considered barren. The results of the on-site humus analysis at all sites confirmed the data obtained from the external laboratory. They are mathematically proved and significant.\(^5\)

4.1.2. Results of the self-made humus analysis of all fields

The graph shows the humus portion in per cent. The humus portion of the Seitingen site is visibly lower than the humus portion at the Frittlinger site. The equality of the proportion between the different fields in the self-made analysis in comparison to the analysis of the laboratory points out their reliability.

4.2. Results of the measured humidity in all fields\(^6\)

In the following chart the humidity of the cup plant and corn fields is shown. The figures represent the average of five separate measures on each field. The concutibility was always documented as well which might be an error source but was always low enough.\(^7\) During field measurements, the temperature of the soil was also documented. On the cup plant fields these values were always a little lower than on the fields with corn. The reason for that is that cup plants cause more shadow due to their close growth. Also, the water that evaporates from their cups causes lower temperatures which both has a positive impact on the soil and the soil biota especially in dry and hot periods.

---

\(^5\) They will be shown in the interviews.

\(^6\) Because of the limited amount of space only a few charts are shown. The other ones are brought to the competition.

\(^7\) The exact data will be provided in the interviews such as the measurements in Ostrach which confirm the ones in Frittlingen.
On the 24 July 2020 during a long hot and dry period the humidity of the corn field differed in relation to the depth much more than that of the cup plant field. The humidity of the corn field at the depth of 40cm was at 45%, which is two times higher than at 10cm depth. In contrast to that the humidity at the two depths in the cup plant fields was almost identical. That shows that corn uses more water from higher layers. In contrast the cup plants use water from both layers and even a bit more from deeper layers. After two more days without rain the humidity of the corn fields was even lower in both layers, although a higher drop off was noticeable at 10cm depth. That implies that corn used its water not anymore only from 10cm depth but also from 40cm depth, but still more from 10cm depth. In general, sun or wind can cause a dry 10cm layer too but as both plants had to deal with the same weather this impact is systematic and the difference in humidity is mainly induced by the plants. The humidity of the cup plant fields had risen a little despite the aridity. The reason for that is that the cups of the cup plant leaves can, for example, absorb morning thaw and also cause a more humid microclimate. Till 01 August 2020 the cup plant fields humidity was in general more uniformly in relation to the layer than the corn fields one although it also differed in cup plant fields soil.

Up to 1 August 2020 there was a long hot and dry period (longer than the period until 24 July 2020). This period caused dry soil in both fields. In the corn field the humidity at 10cm depth was almost constant but at 40cm depth it had fallen to the same level as at 10cm depth. This development was already indicated on 26 July 2020: corn used water from the higher layer until the tension of the remaining water in the fine pores was too high and the plant could not use it anymore. In this case the corn plants started using water from the deeper layer. That the highest layer has continued to get dryer in the following days was caused by evaporation. Now the humidity of the cup plant field differed more in respect to the different layers than the corn fields one. At 10cm depth the soil of this field was even dryer than the corn field and at 40cm depth it is more humid. That is because the cup plants still use their water uniformly from all layers. The 10cm layer was dryer than the corn field one because the cup plants still used water from this layer as well and corn completely stopped using water from 10cm depth. The deeper layer was more humid on the cup plant field because corn took all of the needed water from the depth of 40cm at this point but the cup plant still used both layers, not only the 40cm deep one.
The next two measurements were made after a heavy rainfall which interrupted the dry period. The rain caused a higher humidity on both fields and both layers although the deeper layers were less humid than the higher ones. That indicates that both plants are able to hold back some water and avoid fast percolation. But still the soil in the cup plant field was a little more humid which indicates that it was able to hold back water a little bit better. Two days after the heavy rainfall the soil in both fields was more arid than directly after the rain. Both plants were able to absorb a part of the water. The cup plant field was more arid than the corn field which shows that the cup plants can absorb more water and do it faster.

The measurements on 29/30 September 2020 were done to look at the effects of the cup plant harvesting and on 04 October 2020 the corn field harvesting. Both harvests had no immediate impact on the soil water on the day after the harvest. This is shown by the similarity of the figures from the different dates. A possible impact cannot be shown with these measurements because the soil was not ploughed yet and no heavy rainfall happened since the harvest.

Altogether the cup plant uses water more uniformly from the different layers which causes less variability in the soil water even in dry or hot periods. That has a positive effect on the soil biota. After a heavy rainfall the cup plant seems to be able to hold back the water a little better than corn and it also absorbs the water a little faster than corn. The harvest of both plants has no immediately noticeable impact on the soil water.

4.3. Results of the measured humidity in the experimental boxes

![Humidity Measurements Chart]

Figure 9: Results of the humidity measures in the boxes (arithmetic mean) from August – December; horizontal axis: time; vertical axis: humidity [%]

The charts above show the humidity measurements of the experiment boxes. It should be mentioned that the weather was arid until the 06 October 2020. After this date there was always enough water for the plants available. This difference leads to two separate analyses. In the drier period, the layer at 30cm depth was the...
driest one in each box. The figures differed between 5.1% (reference-box) and 38.2% (reference-box after a few little rainfalls). The fact that also the reference-box had a dry highest layer indicates that this aridity was caused by potential surface evapotranspiration (induced mainly by sun and wind). In the deeper layers the reference-box was more humid than the boxes with corn or cup plant because the plants used water from these layers. This observation can be made for example at the depth of 60 cm: on 30 August 2020 the difference between the reference-box (35.5%) and the cup-plant/corn-box (24.4%) was huge. This relation stayed almost uniformly until 06 October 2020 and was induced by the water shortage. That is also the reason why the chart of the reference-box had more up and down turns in this period. Rainfall induced this variability in the reference-box but in the other boxes the plants absorbed this water immediately and the soil water reached the same level as before quickly. This observation can also be confirmed by the measurements in Frittlingen.

At first glance it also seems that cup plants in general absorb more water than corn because the soil in the cup plant-boxes in this period was more arid than in the ones with corn. But that only seems like that because of the cup plant’s physiology. It is sometimes impossible to separate the roots of different cup plants. As a result, in two cup plant-boxes were more than just one plant and thereupon their water use was higher than the water use of singular plants which lead to a higher arithmetic middle. If the box with the singular cup plant is compared to the corn-boxes it can be asserted that the water use of corn and cup plant is roughly similar.

While evaluating the period after 06 October 2020 it can be said that the layer at 30 cm depth was still the most arid one. As this was the case in all of the boxes a part of the reason is once again the potential surface evapotranspiration. But then the difference between the highest layer and the others in the corn-box was much higher than in the other boxes. That leads to the conclusion that the arid top layer had a further reason: corn absorbs its water mainly from the highest layer. This data once again confirms the field measurements in Frittlingen. In the boxes with cup plants the layers at 120 cm and at 90 cm depth were both less humid than the layer at 60 cm depth. In contrast to that the three layers were very similar in all other boxes. This difference is based on that they also used water from lower layers such as 120 cm and 90 cm and as a consequence they got a little more arid. This observation seems to disagree with the data from Frittlingen at first glance because cup plants have used their water from the 40 cm layer there. But it must be considered that this variability can be provoked by the different soils of Frittlingen and the boxes. And in both cases the cup plant had also sourced its water from deeper layers than corn.

On the whole, cup plants and corn are in need of more water in dry periods. In non-arid periods the cup plant uses water also from the 90-120 cm deep layers. Corn uses its water mainly from 30 cm depth and only a little from deeper layers. The high variability in the humidity of the reference-box points out that soil is exposed to wind, sun and rain and is susceptible to high soil water variability without plants which both buffer this variability. Moreover, all observations of field measurements could be proved with the boxes except for those about shadows’ influences on micro climate because a simulation was not possible with single plants.
Figure 10: Results of the two first heavy rainfall experiments; horizontal axis: time after the heavy rain; vertical axis: arithmetic mean of the humidity in soil in %. Reference (continuous line); cup plant (dotted line); corn (dashed line).

During the following heavy rainfall experiments, 40l were poured into each box, which roughly equates to a heavy rainfall with 40l/m². The first heavy rainfall experiment took place when both plants had already been in the boxes for 88 days and had developed roots which reached almost one meter deep into the soil. The chart shows that in each box and each layer the humidity has risen after the rainfall. But the degree of the humidity difference was not uniform. After one hour, the humidity increase in each box was higher in the deeper layers. That leads to the conclusion that some water always percolates into deeper layers and is held back little by little on its way. But water that percolates too fast/is not held back always sweeps out important nutrients such as nitrate. If water with these substances can not be absorbed then the plants cannot use the nutrients anymore and they wind up in the groundwater. That is the reason why it is important to observe the layer of 120cm depth. Water that arrives in this layer would be outside the range of plants in nature and would wind up in the groundwater. The humidity in this layer (120cm) has risen in every box although the increase was higher in the corn boxes than in these with cup plants. That leads to the conclusion that cup plants could absorb more water in higher layers than corn. Also, the cup-plant-boxes were the only ones were the humidity has risen between one and four hours (again at 120cm depth). That shows that the cup plant was able to hold back water which percolated slower and later than in the other boxes. That gave the soil the chance to save the water. Corn was also able to hold back some water: in the layers at 60cm and 90cm the humidity increase during the time between one and four hours.

Immediately before the second heavy rainfall experiment the cup plant was harvested which means that the plants were cut off about 10cm above the ground which is similar to how they are treated on real fields. In the cup plant-boxes the humidity has risen in the deeper layers between one and four hours. This increase was regular during both time periods. In contrast to that the humidity in corn-/reference-box has only risen during the first hour. That shows that cup plants held back the water better than corn and the reference-box also after the harvest. Thereby, they make it possible that the water can be saved in the soil pores. However, the cup plant has absorbed less water than corn because after the harvest there was no plant left that could require and transpire the water.
Immediately before the third heavy rainfall experiment the corn was harvested. That means that the corn was cut off just like the cup plant before and then the soil was ploughed to simulate the situation on the fields. Both harvests took place at the same time as on the real fields. That process had a huge impact on the humidity: in the higher layers, the humidity did almost not rise after the rainfall and the water percolated almost completely and very fast. The only layer where the humidity has risen remarkably is the 120cm layer. In contrast to that the humidity of the different layers in the cup-plant-boxes were more similar. Also, the humidity increase at 120cm depth was less than twice as little than in the corn boxes. In the reference-box the humidity has risen more than in the cup plant-boxes but less fast than in the corn-boxes. The reason for that is, that the ploughing process in the corn-boxes has destroyed the natural soil fabric which leads to the water to percolate even faster than in the reference-box where sun and wind seem to cement the highest layer a little. The corn could not balance this disadvantage, unlike cup plants, because of its annuality. The forth heavy rainfall experiment took place in spring when the cup plants and the in November 2020 seeded alfalfa just began to grow. Alfalfa was seeded in the corn boxes to simulate green manuring because farmers often use corn and green manuring in combination to avoid long periods of lying waste fields. In this experiment, it was observed whether alfalfa was able to hold water back after a heavy rainfall. As the chart shows it is. The rising of the humidity in 120cm depth was roughly uniformly in the corn- and cup plant-boxes. Alfalfa can hold water back as good as cup plants. The only difference between the two plants is that alfalfa stopped the water in 60cm depth which is showed by the high humidity difference in this layer. In contrast to that cup plant held more water back in 90cm depth which is caused by their different root lengths. Altogether, cup plants can hold water clearly better back than corn. This difference is especially significant after the harvest. The negative aspects of corn can be avoided in some periods by growing alfalfa as a green manuring.

4.4. Results of the nitrate measurements

Alltogether 93 nitrate samples in fields and the boxes were taken. The different nitrate concentrations were analyzed and the results were often unequal. These variations demonstrate the high locality and temporally natural spread of nitrate. (The exact figures of all nitrate measures will be brought to the interview). Therefore, the leaching of nitrate becomes even more relevant.
4.5. Comparison of the photosynthetically active leaf areas
After measuring the leaf surfaces and calculating the average, the answer on the question how far the growth of the cup plant on a poor soil differs between planted seedlings and cup plants which were sown by seed, can be given. For the cup plant which was planted as a seedling, the average leaf surface is the highest with 23,03cm². The sown by seed cup plant has a leaf surface of 13,79cm² on average. This result demonstrates clearly that planted seedlings have an advantage towards the sown cup plants on poor soils. The average leaf surface of the cup plant which was undersown with the green manuring plant alfalfa amounts 15,9cm². This shows that the cup plant grows better in combination with alfalfa than if it is being sown on its own. This could be due to the fact that the alfalfa avoids other competing weeds. Furthermore, another, more humid microclimate which is produced by the taller and denser growing alfalfa is a possible explanation for the improved growth of the cup plant. Also, the roots of the alfalfa simply loosen the soil and create better conditions of growth. A comparison between corn and cup plant cannot be done with the same method because the proportional relation between leaf surface and phytomass is only given for the same plant species. Nevertheless, visual conclusions can be done. Even though the corn could grow on the barren soil, dwarfism could be seen clearly. The plants were around one meter smaller than corn plants on other fields. The corn also had chlorosis, dried out leaves and rarely cobs. The reason for this can be found in the fact that corns are strong uptakers and have a high demand for nutrients which were missing in the given soil. The cup plants were also a bit smaller than usual for the first year but the difference was still not as extreme as for the corn. In conclusion, the cup plant does cope better with poor soils. This is connected with its lower demand of nutrients which could already be seen in the results of the soil analysis. The cup plant is therefore the better option for the reintegration of barren soils into agriculture. This finding is important because crops which can be used for the reintegration of barren soils are essential because as seen in our water experiments, leaving the ground fallow leads to an increased leaching of nutrients and has several consequences for the environment. In the second year of vegetation, this thesis was confirmed. The cup plant sprouted by itself and doesn’t distinguish that much from cup plants which grew under optimal conditions anymore. Herein, the advantage of the cup plant as a permanent crop becomes apparent.

5. Conclusion
A reasonable use of soils and moderate, precise fertilization can play a major role for climate change mitigation and protection of water bodies. In summary, the measured parameters show that cup plant is not a “wonder plant” in comparison to corn, owing to the lower energy yield, the permanent field occupancy and the expensive acquisition. However, the cup plant does have ecological advantages due to its permanence. The cup plant has a positive impact on soil waterbalance, alleviating the impact of drought and heavy rainfall. Moreover, the plant itself is able to collect and retain water. Thus, nutrient leakage especially of nitrate is reduced significantly, when applying a moderate fertilizing strategy. Corn, on the other hand, increases the risk of nitrate leakage due to heavy fertilization in combination with root decomposition. Moreover, when
cultivating corn, soil is laid bare between cultivation periods and soil structure suffers from the use of heavy machinery, such as ploughs, which cumulatively leads to an increased risk for erosion. This could also be observed during the simulations of heavy rainfall in the trial boxes. The effect became specifically apparent after corn harvest: water ran through the soil layers unhindered and soil erosion and nutrient leakage could not be prevented at all during this period. This improved significantly during the last simulation of heavy rainfall, which was timed after germination of alfalfa, that was sown into the corn boxes as catch crops intermittent to corn cultivation periods. We conclude that it is advisable to use green manure subsequently to corn cultivation, to at least partially prevent nutrient leakage after harvest and thus protect the surrounding environment from nitrate leakage into waters. Additional positive effects of green manuring have previously been well-documented, such as enhanced soil aeration, a more controlled nitrate delivery due to natural decomposition, and decreased need for synthetic nitrate fertilizer or manure. The green manures overall positive effect on soil health had a positive impact on the growth of sown cup plants. This could be seen in the experiment on the barren soil in Seitingen, where cup plants undersown with alfalfa produced substantially more biomass during the observed period than cup plants cultivated alone. Cup plants, that were pre-cultivated in humus-rich soil before planting in freeland grew the largest phytomass. However, this cultivation method is not economically feasible for farmers. The next best result was achieved by cultivating cup plant together with alfalfa. This allows farmers to use the more economic approach of directly sowing cup plant in their fields, while preserving the majority of increase in biomass growth, compared to sowing cup plant only.

Generally, cup plants were able to cope better with unfavourable growth conditions on poor soils compared to corn. This may make the cup plant cultivation a valuable option when reintegrating barren soils into agriculture. Cup plants suffer from drought stress just as corn plants which could be visually observed as dried-out leave mass. However, the ability of collecting and retaining rainwater in its conjoined leaf bases, as well as its dense growth produce a more humid and cooler microclimate at the soil surface and in near-surface soil layers. Especially during longer periods of drought, these features create a considerable advantage for the plant’s survival and on the soil health. For instance, the soil in the cup plant field at the Frittlingen site showed a slightly higher humus content compared to the corn field, in accordance with current literature [5]. This provides a better basis for active soil life, water retention and carbon storage, which ultimately is favorable in the context of climate change mitigation and water protection. Even if the measured difference in humus content seems rather small, it must be seen in context of the short study period and likely indicates a positive tendency, which may increase with constant cultivation of cup plants over years. Humification is a slow process and occurs over long time periods, while the studied cup plant field has only been cultivated for eight years so far.

In contrast to corn, the cup plant remains alive after harvest and generally no parts decompose between growth periods. However, the humus content is still higher, likely due to a generally more constant turnover of nutrients compared to corn and fewer disruptions by mechanical interventions. When cultivating cup plant,
fewer agricultural interventions are needed and unlike for corn, there is no need for the annual use of herbicides or insecticides, which makes the cultivation of cup plant more sustainable compared to the cultivation of corn. Furthermore, cup plants enhance the biodiversity, by supporting healthy micro- and macrobiotic life underneath, as well as over ground, e.g. pollinators. Cup plant is very attractive to for instance bees and honey from cup plants is already being commercialized.

In summary, cup plant representas a more sustainable alternative to corn, when cultivating plants for bioenergy production, due to its balancing influence on soil water and nutrient cycles and in turn the positive effect on climate change. In consideration of economical and ecological aspects, the cultivation of cup plants is suggested primarily on Ecological Focus Areas, on slopes, in nitrate contaminated areas and flood regions, on forest edges as well as on barren and depleted fields, which represent too unfavourable conditions for corn.

6. Public outreach and education

Figure 13: A cover of our children’s book; B – C our game “Simaland – the biogas challenge”

To communicate the obtained results on soil health to a wider public, especially to children and young people as future consumers, managers, scientists and main victims of climate change, a children’s book has been written to playfully raise awareness. The protagonist experiences different adventures which are all connected to the topics soil health and water cycle. The book is available on the market since mid-March 2021 and has already been sold over a hundred times (see also: www.bneamikg.de → Projekte).

Furthermore, an educational game was created incorporating the results of this project. This game is currently used at our school. Beyond those outreach actions, we will integrate our trial boxes in our new school garden and an outdoor museum with educational approach.

7. Outlook

As soon as the corn is established in the trial boxes, a defined nitrate experiment will be done. The aim is to compare the nitrate filtration capacities of the two plants excluding possible disruptive factors and to simulate the situation on actual fields after fertilization. At the end of summer 2021, a comparative analysis of the phytomass of the two-year-old cup plants will be carried out at the Seitingen site, at the timepoint of the first harvest after establishment.
8. Bibliography


[8] https://op.europa.eu/de/publication-detail/-/publication/541f0184-759e-11e7-b2f2-01aa75ed71a1


[20] Discussions with agriculturists of our region (Mr. Benne, Ms. Mink, Ms. Kipp) since Mai 2020