FOSTERING SUSTAINABLE FEEDSTOCK PRODUCTION FOR ADVANCED BIOFUELS ON UNDERUTILISED LAND IN EUROPE

D2.3

FEASIBILITY STUDY GERMANY

AGRONOMIC FEASIBILITY

PART I – CASE STUDY ACTIVITIES ON DISUSED SEWAGE IRRIGATION FIELDS

PART II – CASE STUDY ACTIVITIES ON RECLAMATION SITES IN THE EASTERN GERMAN LIGNITE DISTRICT (LUSATIA)

ANNEXES

FIB

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PART 1 - CASE STUDY ACTIVITIES ON DISUSED SEWAGE IRRIGATION FIELDS

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List of abbreviations

AC	*ante Christum* (before Christ)
ACS	alley-cropping system
AFS	agroforestry system
Ahj	Ah horizon (mineral soil), topsoil with initial accumulation of soil humified organic matter, at or near the surface
As	arsenic
a.s.l.	above sea level
B	B horizon (mineral soil, subsurface), with evidence of pedogenesis or illuviation
BD	soil bulk density
$CaCO_3$	calcium carbonate
$CaMg(CO_3)_2$	dolomite
CaO	calcium oxide
CAP	EU Common agricultural policy
CE	cereal equivalent
Cd	cadmium
CHC	chlorinated hydrocarbons
Cr	chromium
C_t	carbon (total)
Cu	copper
d	day(s)
DM	dry matter
ET	evapotranspiration
EU	European Union
€	euro
FC	field water capacity
Fe	iron
FeS_2	ferric sulphide
FIB e.V.	Forschungsinstitut für Bergbaufolgelandschaften e.V.
FORBIO	field experiments and investigations within FORBIO project
FW	fresh weight

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g	gram
GAP	good agricultural practices
ha	hectare
Hg	mercury
HNO_3	nitric acid
i.e.	*id est* (that means)
K	potassium
kg	kilogram
km^2	square kilometre
kWh_{el}	kilowatt hour electric power
LSG	legally-binding protected landscapes
m	meter
m^2	square meter
Mg *(in the context)*	megagram (= tonne, 1,000 kg)
Mg *(in the context)*	magnesium
mg	milligram
MKW	aromatic hydrocarbons
mm	millimetre
Mn	manganese
Mo	molybdenum
N	nitrogen
n.d.	not determined
Ni	nickel
P	phosphorous
PAH	polycyclic aromatic hydrocarbons
PAWC	plant available water storage capacity of the soil
Pb	lead
PC	profit contribution (margin)
PCB	polychlorinated biphenyls
PCDD	dibenzo-p-dioxins
PCDF	dibenzofurans
pH	pH value

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PHC	petroleum hydrocarbons
SOM	soil organic matter
SP	EU single farm payments
SRC	short-rotation coppice
SRF	short-rotation forestry
SQR	soil quality rating index
TOC	total organic matter
yr	year(s)
Zn	zinc
ºC	degree Celsius
%	percentage
Ø	average

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Landscape characteristics – geomorphology and climate

The study area *Berlin & Brandenburg* is part of the *Northeast German Lowlands* and of *Quaternary* origin. Landscape-forming are the *Weichselian* and *Saale* glacial periods (*Lusatia*, Stackebrandt & Franke 2015, Figure 1 and 2). Hence, the agricultural soils of the region are dominated by fluvial and glacial sands. The overall yield potential is quite moderate. Only 20 % of the arable land take high-yielding sandy loams and loess soils (Table 1, Figure 5). Widespread soil types are (podzolic) brown earths (*Dystric Cambisols*) and leached brown soils (*Luvisols*).

Located in the transition zone from the Western sub-atlantic to Eastern sub-continental climate, there is a moderate rainfall and temperature gradient (Table 1, Figure 3). Whereas the annual precipitation in the Northwest parts amounts 700 mm it drops to 500 mm in the Southeast. Contrariwise, the mean annual air temperature raises from 7.0 to 9.5 °C (Kopp & Schwanecke 1994,). Although half of the rainfall is during the growing season, even in climate *"normals"* there is a climatic water deficit in the vegetation period of 125 mm to 225 mm (MLUR 2003, Figure 4). Thus, water availability becomes the limiting resource for cropping, especially on sorption-poor and groundwater unaffected soils of the plateaus. In other words: on 90 % of the farmland there is an average water requirement in the vegetation period of about 4 mm per day while precipitation supplies only 2 mm. Common water shortage in early summer leads to a serious loss of vitality, yield depression and quality loss of the harvest products - yield forecasting gets difficult. Overall dry summers, like 2003, 2006 or 2015, result in a yield reduction of 30 to 40 % compared to the long-time average (MLUR 2004, MLUV 2007).

With its dry and warm summers, the region is considered as one of the most climate sensitive areas in *Germany* (Spekat et al. 2007, LUA 2010). Already compared to the 1960s there is a significant increase of the annual mean temperature by 1 °C. Even moderate climate scenarios for the *"far future"* (2071-2100) indicate a further warming by 2 °C. In the worst-case annual precipitation declines to less than 500 mm in the southern parts of *Brandenburg* (Knoche et al. 2012a). Such vulnerable to climate change impacts, the frequency of extreme weather events with very unfavourable effects on plant growth will increase (Gerstengarbe et al. 2003, Wiggering et al. 2005, Linke et al. 2010).

TABLE 1: A SHORT LANDSCAPE CHARACTERISATION OF THE CASE STUDY REGION *BERLIN & BRANDENBURG*

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Main landscape / Natural region	- *Northeast German Lowlands* (50 - 200 m a.s.l.) - landscape-formative: sediments of the *Weichselian* glacial period (115,000 -11,600 yr AC) and *Saale* glacial period (304,000 - 127,000 yr AC), with a diverse inventory of moraines, plateaus and reservoirs, periglacial and post-glacial dunes, sand drift areas, glacial spillways and lowlands with fens
Regional climate	- Western sub-atlantic to Eastern sub-continental climate - mean annual temperature: 7.0 to 9.5 °C - amplitude of average monthly temperature: 20.0 °C - average rainfall: 500 to 700 mm yr^{-1} - climatic water balance in the vegetation period: -50 to <-200 mm
Site conditions	- *Quaternary* glacial and fluvial sands and loamy arable lands with a low to moderate yield potential, less than 20 % of the arable land are of better quality sandy loam and sandy loess soils - sandy-loamy brown earths (*Dystric Cambisols*), leached brown earths (*Luvisols*) and sandy podzols, hydromorphic soils
Potential natural vegetation	- pure beech forests, mixed oak-beech-forests with some valuable broadleaves - Scots pine - sessile/common oak forests - pure Scots pine forests with common birch - alder-ash swamp forests
Agricultural land use	- arable cropping, dry-land farming for catering production and conventional feedstock - forage cropping - pasture farming

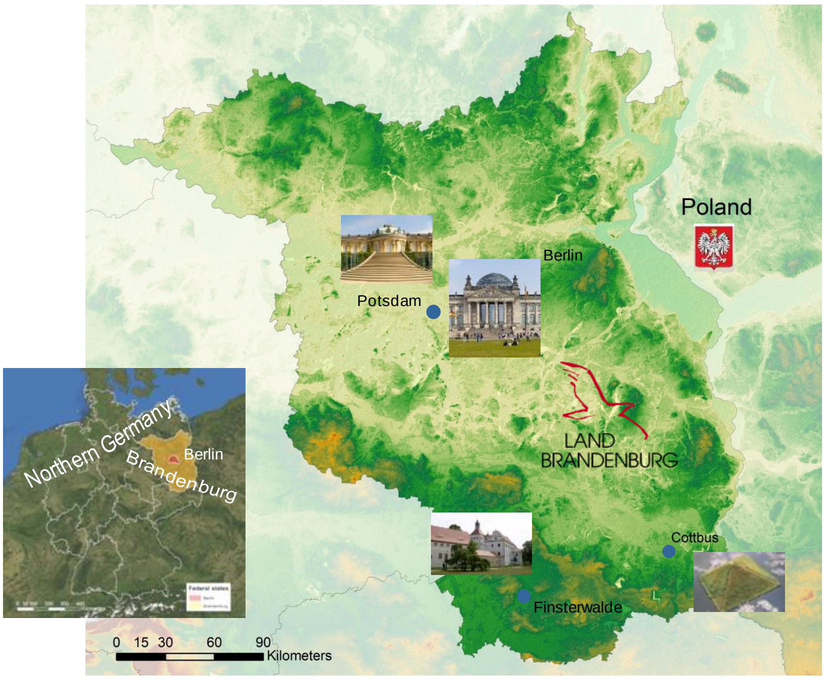

FIGURE 1: OUR CASE STUDY REGION BERLIN & BRANDENBURG IN THE NORTHEAST GERMAN LOWLANDS

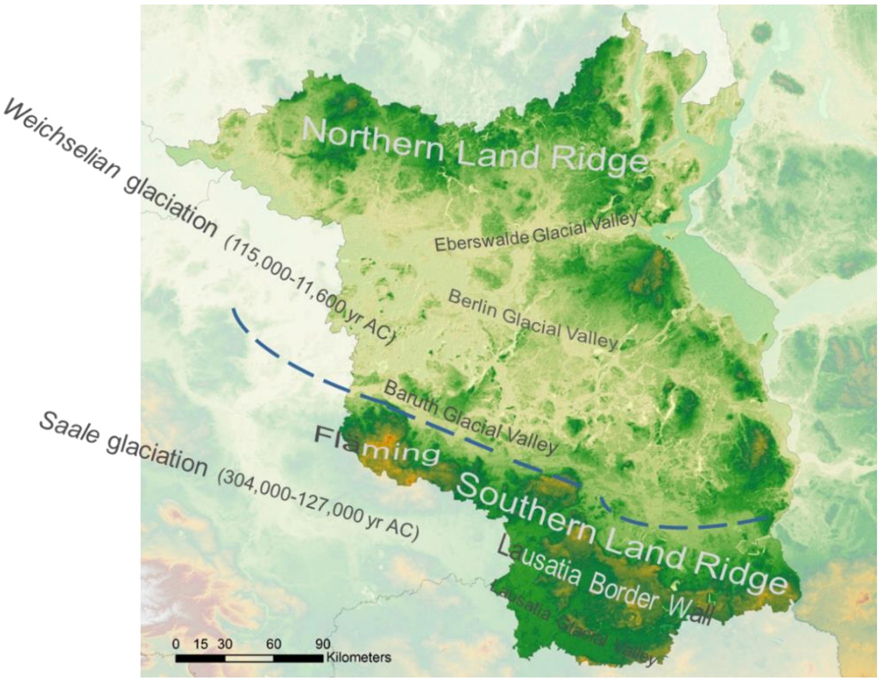

FIGURE 2: REGIONAL TOPOGRAPHY WITH SOME FORMATIVE ELEMENTS OF A TYPICAL (POST)-GLACIAL LANDSCAPE

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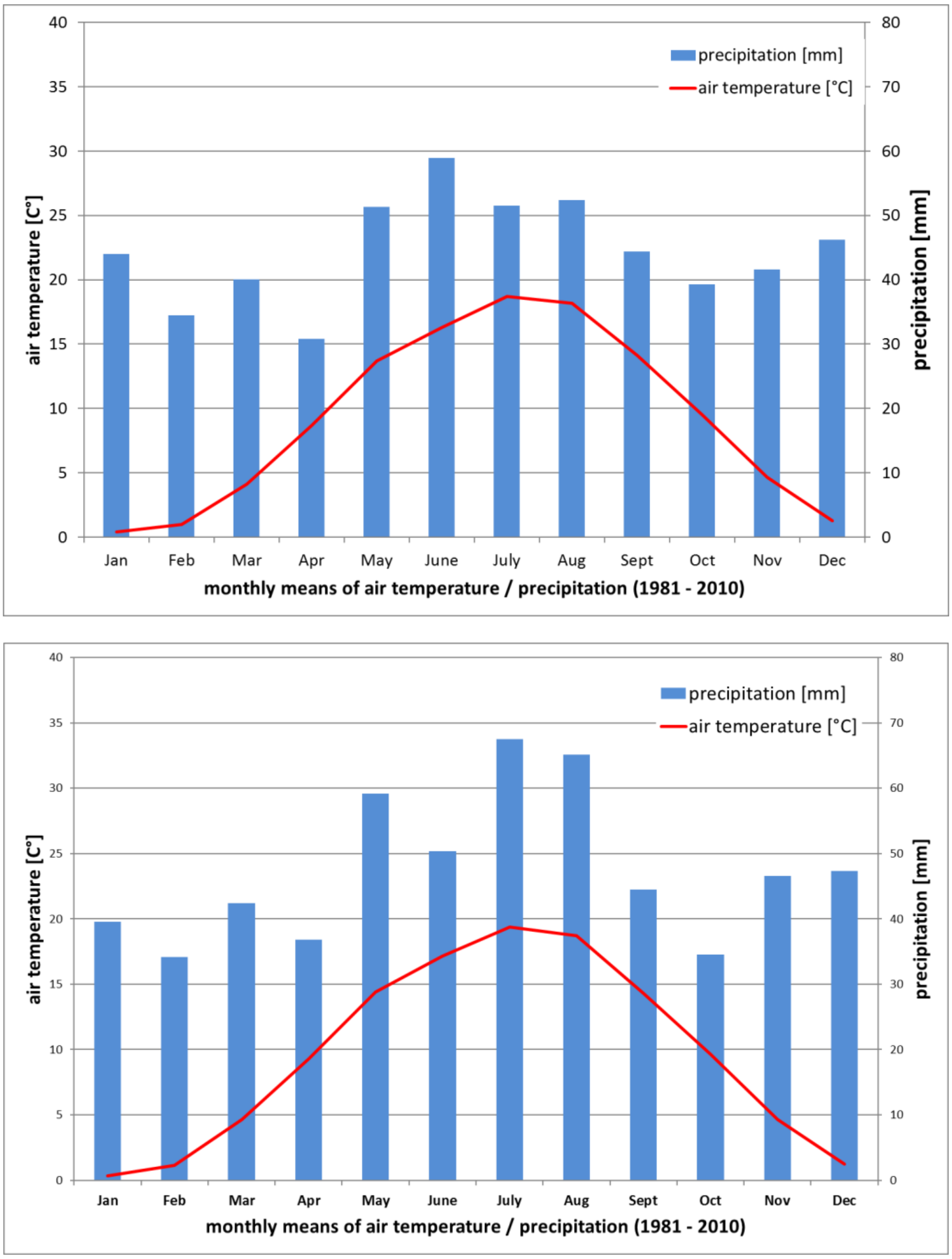

FIGURE 3: CLIMATE DIAGRAMS OF THE WEATHER STATIONS NEURUPPIN (ABOVE, ID 3552) AND COTTBUS (BELOW, ID 880)

long-time average for the *"climatic reference period"* 1981 to 2010, data source: *German Meteorological Service* (2016)

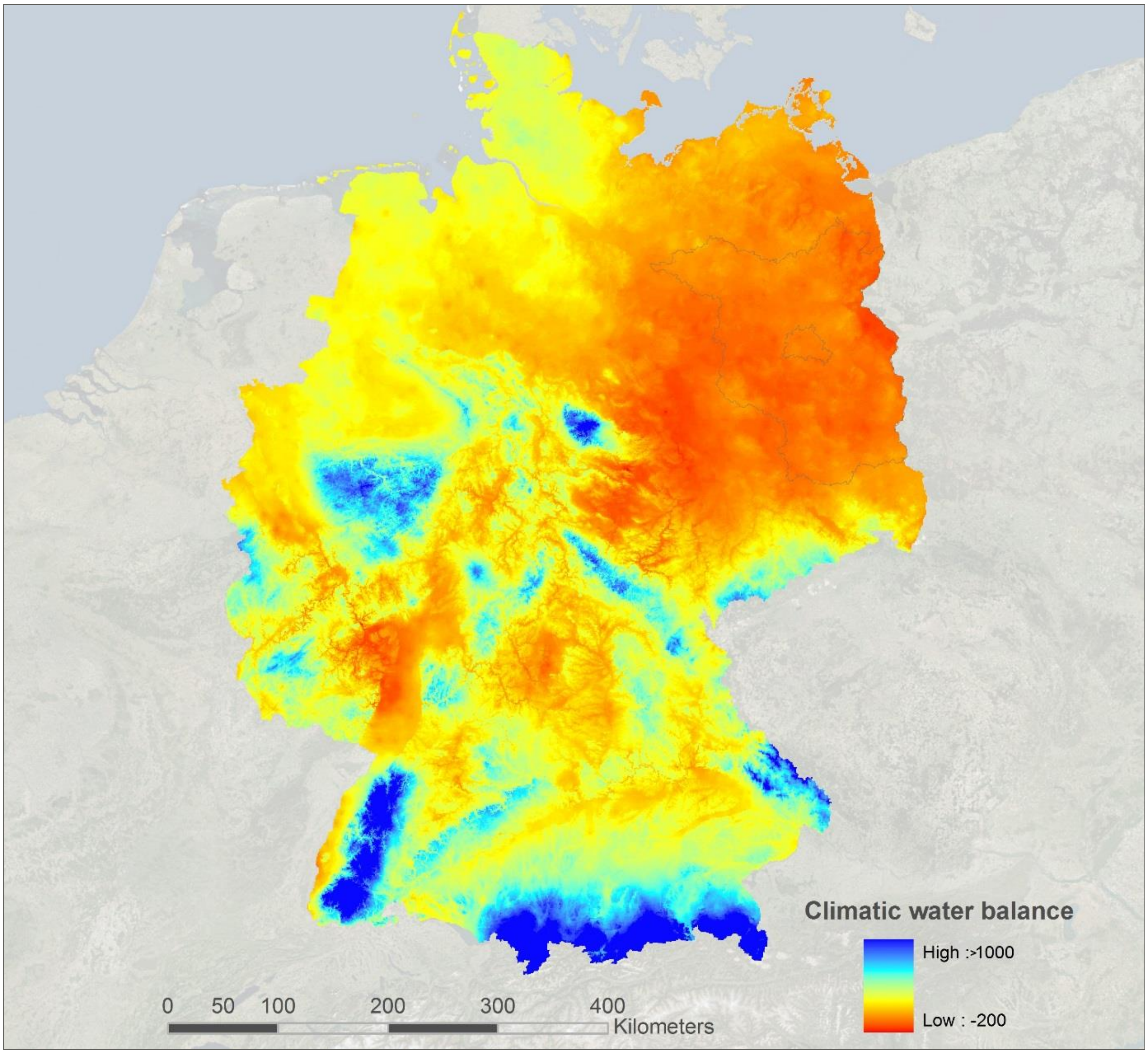

FIGURE 4: AVERAGE CLIMATIC WATER BALANCE IN THE VEGETATION PERIOD (CWB_V)

for the reference period 1971 to 2000, data source: *German Meteorological Service* (2016)

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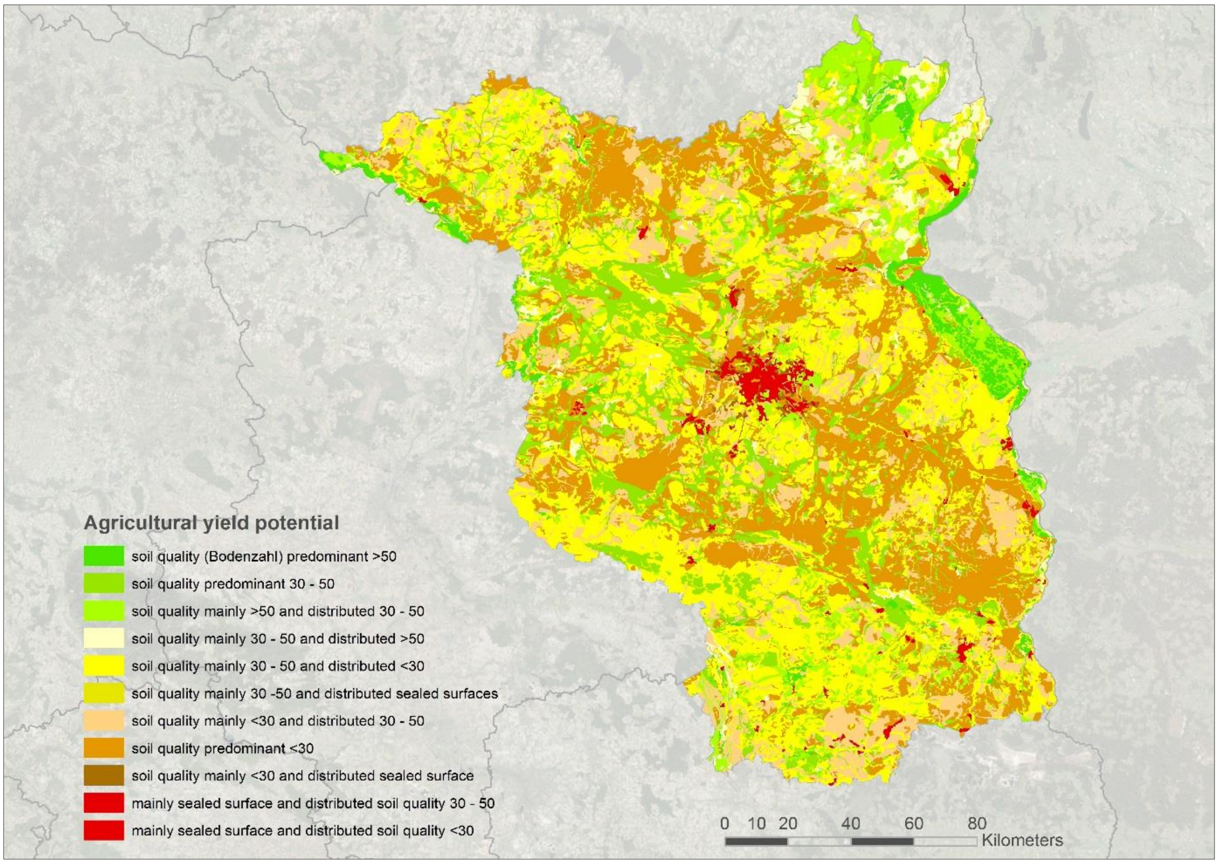

FIGURE 5: AGRICULTURAL YIELD POTENTIAL IN THE CASE STUDY REGION

compiled using the digital data *"Landwirtschaftliches Ertragspotential"* © LBGR 2016, www.lbgr.brandenburg.de

Sewage irrigation fields in *Berlin & Brandenburg*

A short summary on the history

In the late 19th century rapid industrialisation and unregulated urbanisation called for a reorganisation of the urban sewage and waste water management in *Germany* (Hohbrecht 1884). Within a few decades the fast-growing city regions establish quite complex sanitary sewer systems. Thereby, first of all in the *Northeast German Lowlands*, hydrological as well as technical aspects and costs spoke for an irrigation of only mechanically pre-treated sewage water as most promising way for disposal. Since 1873 a network of pipes and pumps was established to collect and transport both untreated domestic and industrial wastewater beyond the city boundaries (Bjarsch 1997, Blackbourn 2006).

An essential presetting for this wastewater cleaning system are good draining sandy soils with a sufficient filter line in the upper lithosphere. Step by step 29,000 hectares of low-yielding farmland were remodelled for irrigation and impounding. Sometimes wastewater treatment lasts for several decades, even until the early 1990s. Nowadays, all irrigation fields are closed and substituted by modern multi-stage sewage-treatment plants (Schmidt 1995).

The remaining 10.010 ha and their spatial distribution

In *Germany* the region of *Berlin & Brandenburg* has by far the most and for the longest time irrigated sewage farms - at the present overall 71 registered sites. Alone in *Brandenburg* they cover 10,010 ha (=0.75 % of the farmland) with a focus on the Northeast and Southern suburban hinterland of *Berlin* (LUA 2003) and the adjacent counties, respectively 9,981 ha according to the last comprehensive inventory of Ritschel & Kratz (2000).

Besides the capital city *Berlin* also the surrounding area of smaller industrial towns in the periphery was claimed for biological waste water cleaning (Figure 6), for example *Frankfurt / Oder* (673 ha), *Cottbus* (160 ha) or *Finsterwalde* (20 ha).

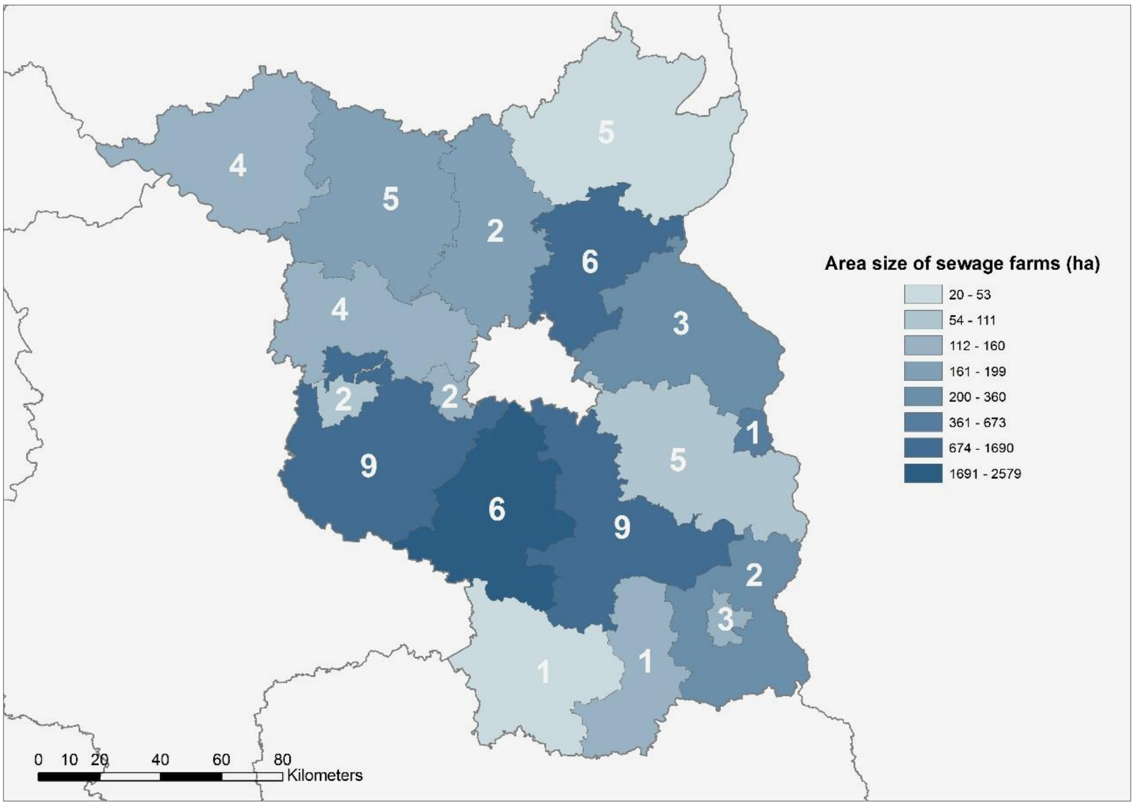

FIGURE 6: DISTRIBUTION OF FORMER SEWAGE IRRIGATION FIELDS IN *BRANDENBURG*, CLASSIFICATION: NUMBER AND AREA PER COUNTY

Irrigation fields – a "*standby*" reserve, ready for energy crops?

In official registers former irrigation fields are classified as *"polluted areas"* or *"potentially contaminated sites"* (Bundesministerium für Justiz und Verbraucherschutz, 1998). However, already 16 % of the area is overbuilt and *"sealed"* by housing, business parks or infrastructure. Still two thirds (6,707 ha) are agricultural land, but with site-specific use restrictions (Ritschel & Kratz 2000, Figure 7). Due to higher operating costs, the comparable low yield potential (marginal land) and an unfavourable field size the extensive pastureland is predominant. Recently, some short-rotation coppices (SRC) have been established.

According to higher-levelled landscape programmes and local land-use plans, approximately 40 % (2,790 ha) of the named farmland should be transformed into other land use forms in the foreseeable future (Figure 8). Especially in the urban surroundings of the fast growing metropolis *Berlin* the municipal zoning plans devote 1/3 as prospective building land, only 5 % are reserved for nature conservation projects. In fact, the suburbs of *Berlin* (the so-called *"flab belt", "Speckgürtel"*, *"Berliner Umland"*) are an attractive residential environment and of interest for housing development companies. In contrast to the rural periphery of the case study region, the population increases due to inward migration (LBV 2015).

On the other hand, still 4,000 ha are *"unplanned"*, i.e. without a designated development objective. However, considering increasing urbanisation, the *"open landscape"* is gaining importance for regional planning, especially with its recreational functions and for the ecological balance (resource protection). Among others: disused sewage farms are looking for an alternative agricultural land use, for example the low-input, second generation biofuel production.

In conclusion, the available potential area for the cultivation of energy crops on former sewage irrigation fields are 1,140 ha to 3,917 ha. These area size potential is calculated without the consideration of ecological, economic and political barriers.

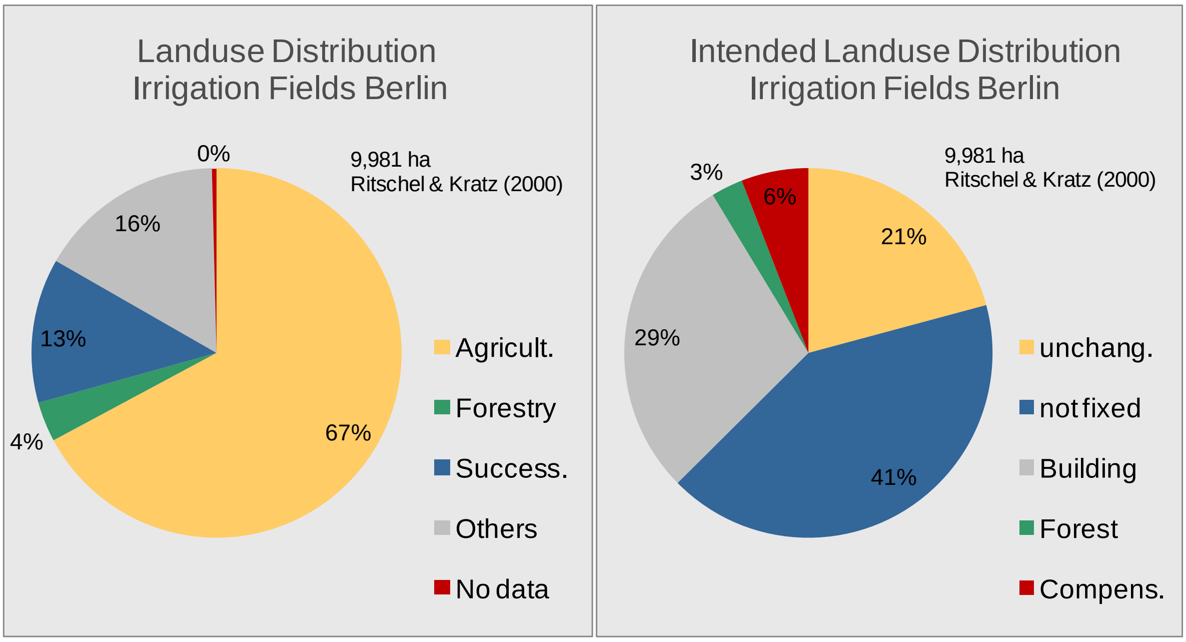

FIGURE 7: CASE STUDY *"BERLINER RIESELFELDER"*: LAND USE AND PLANNING PERSPECTIVES ON FORMER IRRIGATION FIELDS CLOSE TO *BERLIN*; DATA ACCORDING TO RITSCHEL & KRATZ (2000)

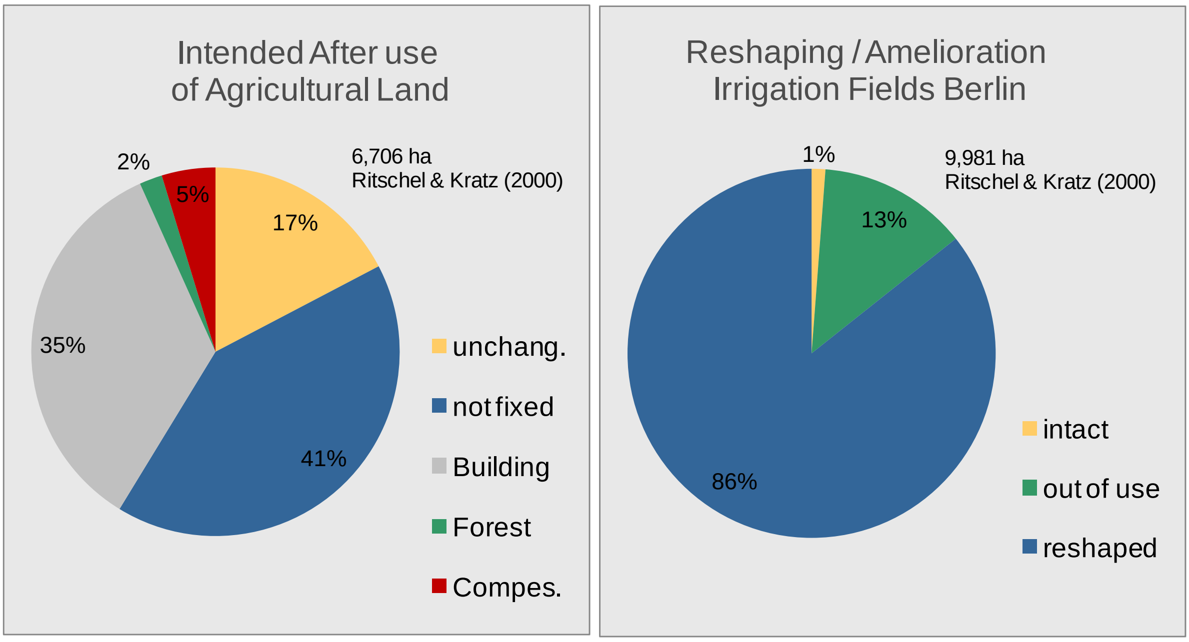

FIGURE 8: CASE STUDY "*BERLINER RIESELFELDER*": RESHAPING AND AMELIORATION OF FORMER IRRIGATION FIELDS AND AFTER USE OF AGRICULTURAL LAND; DATA ACCORDING TO RITSCHEL & KRATZ (2000)

Design principles and structural elements of sewage irrigation fields

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Taking a closer look at irrigation fields, there is always a characteristic combination of structuring elements (Blumenstein 1995), namely: irrigation and infiltration zones, feeding channel system, waste water and mud settling ponds, sludge drying places with the associated infrastructure (Table 2, Figure 9, 10 and 11). First the wastewater reaches a settling basin, where most of the particulate matter sediments. Channels are feeding the irrigation zone, where the nutrient rich (but also polluted) water slowly percolates through the sandy overburden. Finally, the biologically pre-cleaned water flows to adjacent ditches and further recipients.

When the infiltration performance of the individual irrigation zone declines over the years, it`s upper soil layer is excavated and stored on the surrounding dams. Hence, especially the mud of the settling basins and the dams are contaminated with heavy metals or organic harmful substances (Lange 2014). In conclusion, only the irrigation fields in a narrower sense are suitable for feedstock production without an expensive, time-consuming land consolidation procedure, reshaping or amelioration (Figure 12). Thus, the effective, easily available cropping area is approximately 15 % less than the surface listed in the land register (LUA 2008).

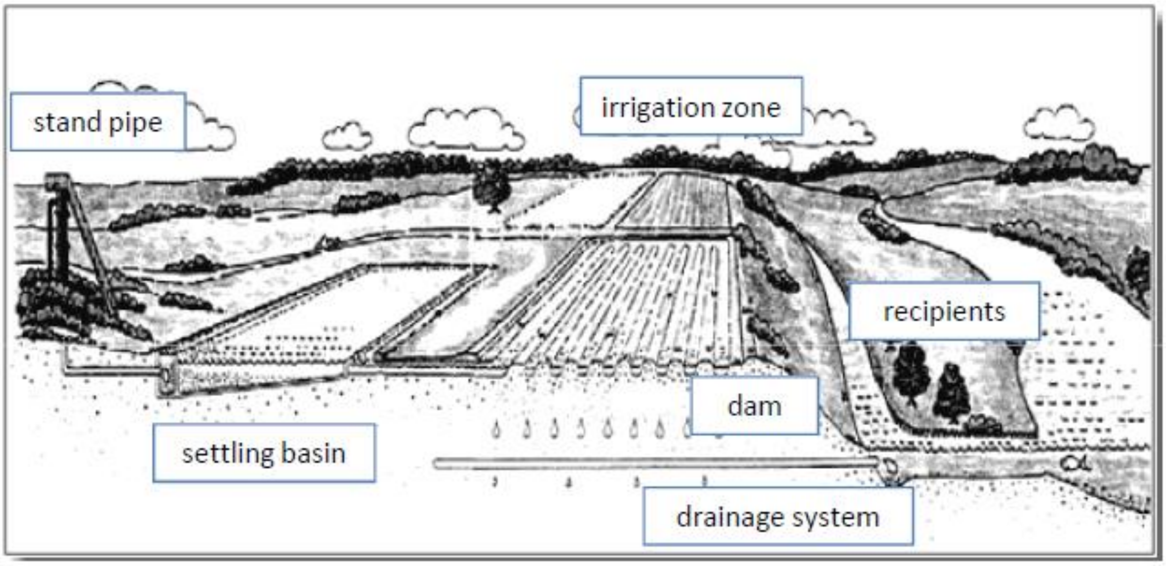

FIGURE 9: TYPICAL STRUCTURAL ELEMENTS OF A SO-CALLED *"RIESELGALERIE"* (FIGURE TAKEN FROM HTTP://WWW.BERLINER-RIESELFELDER.DE, 15.07.2016)

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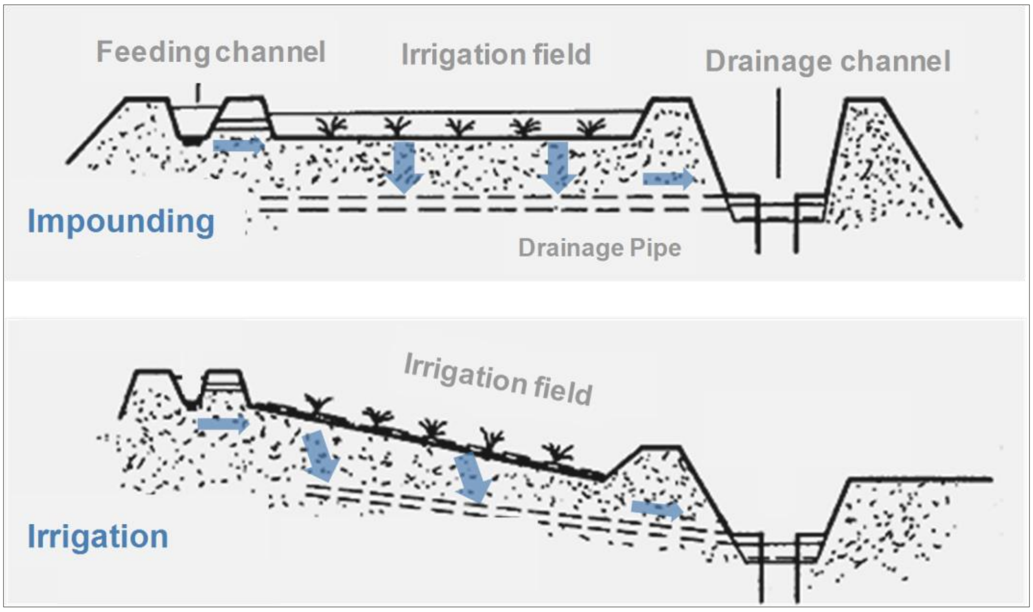

FIGURE 10: DESIGN PRINCIPLE OF SEWAGE IRRIGATION FIELDS, ACCORDING TO ERHARDT ET AL. (1991)

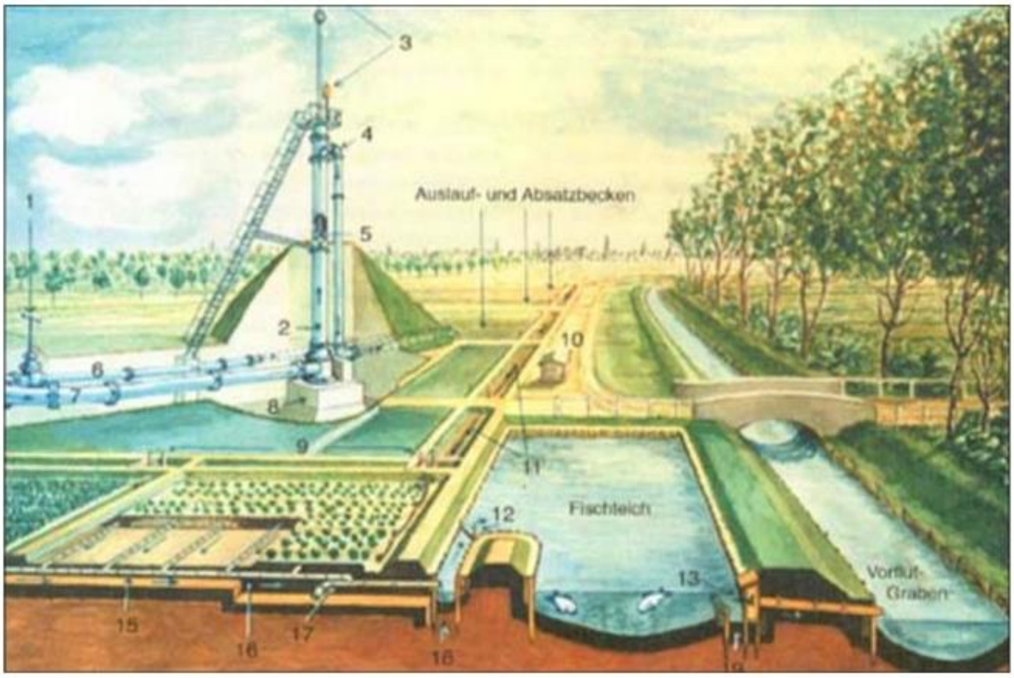

FIGURE 11: A HISTORICAL VIEW ON A SEWAGE FARM NEARBY *BERLIN* (HTTP://WWW.NATURIMBARNIM.DE/PROJEKTE/RIESELFELDLANDSCHAFT-HOBRECHTSFELDE.HTML)

Please note the usage of cleaned wastewater for carp breeding and vegetable cultivation.

TABLE 2: SOME FEATURES OF QUITE TYPICAL SEWAGE FIELDS IN *BERLIN & BRANDENBURG*, BLUMENSTEIN (1995), LUA (2008)

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Feature	Description	Area (%)
irrigation field in the narrow sense	several fields with 6 to 10 separate irrigation zones (0.25 ha each), base slope 0.5 %, bordered by dams (0.5 to 1.0 m)	85
irrigation channel system	connecting and feeding the irrigation fields, ditches with border areas, overall width 4 to 5 m	4
wastewater settling ponds	basins for particle sedimentation (50 to 2,000 m^2) before spreading waste water on irrigation fields	<0.5
mud settling ponds / sludge drying places	basins for deposition of excavated (sewage) sludge	<0.5
infrastructure	depot, farm buildings and roads with border strips, hedgerows, supply pipes and drainage system	+/-10

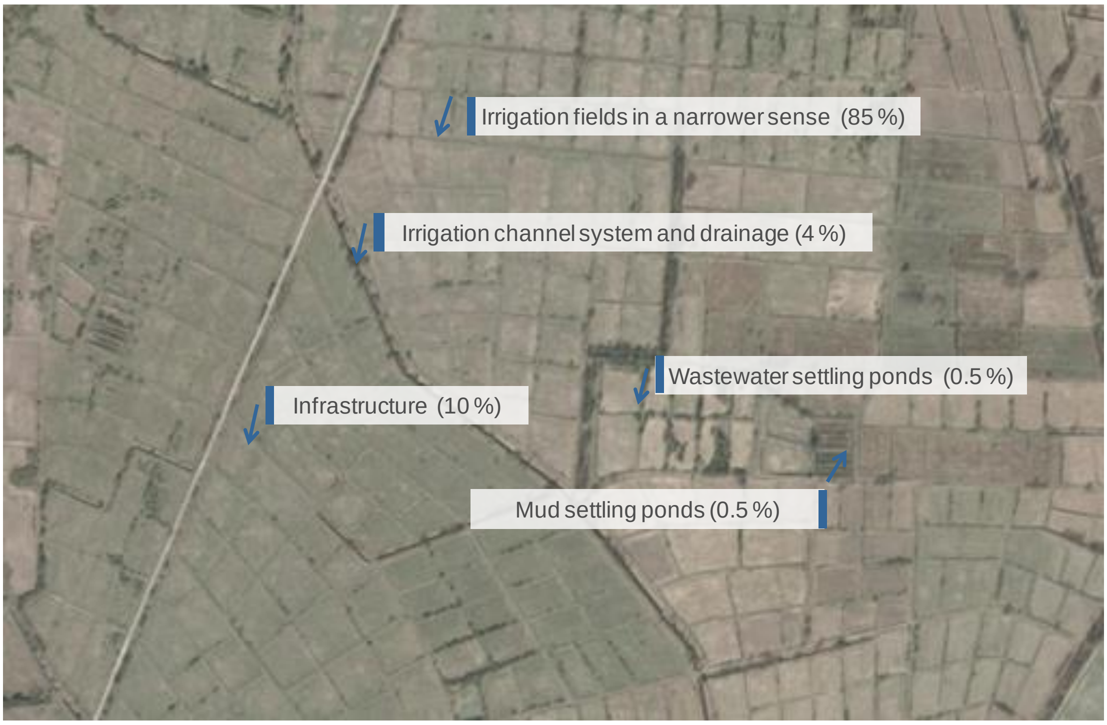

FIGURE 12: THE STRUCTURE ELEMENTS OF A TYPICAL SEWAGE FARM IN THE SURROUNDINGS OF *BERLIN*

Sewage fields outside *Berlin & Brandenburg*

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Moreover, within the scope of a comprehensive literature study LUA (2003) screened data for over 180 sewage farms across *Germany*. Table 3 lists some of the largest irrigation fields outside the study area. In most cases the disused irrigation fields are in municipal ownership. Frequently they are addressed to nature protection or urban recreation areas (*Münster, Freiburg, Dortmund, Magdeburg, Gütersloh*), sometimes a compensation for building in parts (*Freiburg, Hannover*).

Within the local land development plan, there is little scope left for a conversion to bioenergy production or other more traditional agricultural systems. In these areas only some sewage fields of *Braunschweig* are still working, with about 275 hectares settling basins and nearby irrigation farming with mechanical and biological pre-cleaned wastewater. It can be summarised that besides the metropolis region *Berlin & Brandenburg* there is only in the Federal States of *Lower Saxony*, *Saxony-Anhalt* and *North Rhine-Westphalia* a remarkable potential for feedstock on disused irrigation fields.

TABLE 3: SOME SEWAGE FARMS AND CONSTRUCTED WETLANDS ACROSS *GERMANY*, LUA (2003) AND OWN INVESTIGATIONS

Sewage Site (Town)	**Area[1) (ha)]**	**Land use**	**Reference**
Braunschweig	4,600	agriculture, water-cleaning, nature preserve area	Kloss (1996)
Wolfsburg / Vorsfelder Werder	1,500	agriculture, nature preserve area	Boll & Eggers (1987)
Dortmund / Waltrop	680	nature preserve area (IUCN)	http://www.dortmund-holthausen.de
Münster (Westfalen)	540	nature protection, for environmental education, "*nature exhibition*" (IUCN)	Harengerd & Sudfelldt (1995)
Magdeburg / Körbelitz	242	nature preserve area	Meissner et al. (1993)
Freiburg im Breisgau	238	nature preserve area, urban recreation zone	http://www.oeko-station.de
Gütersloh / Pavenstädt	130	agriculture	Bischoff (1992) http://www.guetersloh.de

1) remaining sewage fields, no urban fabric

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Sewage farms – site conditions

Promising rain-fed agriculture…

An important cross-cutting key effect of biological wastewater cleaning is the reuse of nitrogen- and phosphorous-rich organic substances (*"liquid manure")* on otherwise nutrient poor and water limited farmland. Depending on the cultivated crops the fields are irrigated by one to eight intervals over the year (Metz et al. 1991). In this way advanced rain-fed farming made a considerable contribution to the catering of the rapidly growing urban population. In particular, forage legumes and grassland with up to six cuttings per year were cultivated. But also more demanding arable cropping (winter / summer wheat, potatoes or sugar beets) and intensive market-gardening were practised, finally more or less successful. In the optimistic spirit of the age and unbroken belief of technological progress some reports named the sewage farms as a real *"kitchen garden"*. And in fact, double cropping became profitable and the per-hectare yields on some intensively irrigated sewage farms belonged to the highest in *Germany* (Metz 1995).

…and its limitations

Unquestionable, wastewater irrigation leads to a well noticed yield improvement during the first decades. However, longer irrigation periods with excessive loads of nutrients and increasing pollutants are impairing the soil fertility. Already in the 1920s with increasing industrial wastewater there was some evidence for inexplicable yield depression, the so-called *"irrigation tiredness"*, some kind of a *"soil sickness"* (Schwarz 1960). As we know today, irrigation promotes nutrient imbalances and an irreversible degradation of the soil structure (siltation). Both *"hyper"*-trophication and reduced soil aeration cause a considerable plant vitality loss leading to growth retardations and an increasing susceptibility to plant diseases and pests, i.e. wireworms (larvae of click beetles - *Elateridae*).

In addition, hazardous substances of industrial wastewater cumulate in the topsoil affecting both plant growth of sensible species and crop utilisation. For instance, on heavy polluted sites the cadmium concentrations in row crops (like potatoes or sugar-beets), maize and cereals were by 10 to 100 times higher as compared to the surroundings. Grazing milk cows had harmful concentrations in liver and kidney. At last in terms of risk prevention all crops were condemned to be unfit both for consumption and forage (Grün et al. 1990 a, b, Sowa et al. 1992). Not least, hygienic aspects restrictions lead to a termination of any cropping in 1983 (Schmidt 1995).

Sewage farms – a potential for biomass-derived fuels?

After giving up watering most disused irrigation fields were rearranged to facilitate a multiple after-use. But very often there was no sound perspective of land use. Still

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most sewage farms serve as *"reserve area"* for the urban development in extensive land management - *"land set aside"*. Planned and already realised conversion projects comprise a wide range of competing land use forms like housing, commercial investments, recreation areas, wildlife habitats or timber production. Although a pressing issue, there is very often no concrete presetting and the discussion about land management is ongoing (Ritschel & Kratz 2000). Especially sites under municipal ownership are well suited for compensation and mitigation measures according to the legal objectives specified in the *Federal Act for the Protection of Nature*. Consequently, the *Berliner Stadtgüter GmbH* is practicing like that. The municipal undertaking of the city tries to market such remaining irrigation fields to potential stakeholders, for example, the new *Berlin-Brandenburg* airport company. Therefore, already in the early planning stage it is essential to find out which land cover is actually available for bioenergy systems or other environmentally-friendly forms of land use.

A most promising perspective for this *"underutilised land"* of limited production function might be an *"environmentally-friendly"* cultivation with agricultural feedstock (Wilke & Metz 1993, Sobioch 2013, Bhardwaj et al. 2015). According to Metz (1995) about 90 % of former irrigation fields are in principle suitable for non-food feedstock (Table 4). However, in the span of two decades reduced nutrients and limiting water availability turned many rainfed sites into degraded land. Negative ecological impacts can appear by mineralisation of allochthonous organics and the pH controlled heavy metal mobilisation, already affecting the groundwater resources (Schlenther et al. 1996, Hoffmann et al. 1999, Metz et al. 2001). This provides a potential for undemanding and low-input ligno-cellulosic feedstock, like SRC with poplar. They are linked to the expectation that a high biomass production minimises both the seepage water formation and leaching of contaminants. Furthermore, a well arranged management with permanent crops can improve the soil quality by phytoremediation - in fact, a substantial *"upgrading"* of otherwise abandoned land (Metz & Wilke 1993, Hasch 2014).

TABLE 4: RECOMMENDATION ON LAND USE FOR FORMER IRRIGATION FIELDS ACCORDING TO THE BIOAVAILABILITY OF HEAVY METALS, WITH A FOCUS ON SOIL PROTECTIVE REQUIREMENTS, METZ (1995) MODIFIED AND COMPLETED

Contamination level & ecological risk	area %	Recommendations on land use
Low	30	reclamation for a multifunctional after-use: limited agriculture (no direct consumption), urban recreation, building area, green belt, if applicable incorporation of unpolluted soil excavation material

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Medium	60	monitored restoration for feedstock production, energy crops, i.e. silage maize, *Sudan* grass, *Sorghum*, woody biomass, oil seed crops, lucerne, waste land afforestation, nature preserve (succession, *"open land"*)
High / very high	10	sealing of the surface (encapsulation), designation as industrial or business park, storage site, waste dump, no plant cropping, but in *"worst case"*: soil replacement

Sewage irrigation fields – a *"second-hand"* landscape

Up to 100 years of intensive waste water irrigation results in irreversible changes of the soil morphology and soil chemical properties. Looking back, before irrigation most sites were under an extensive agricultural management, corresponding with the natural low site productivity. More than 80 % of the sewage farms were originally classified as nutrient-poor sandy soils of the glacial outwash plains. Such coarsely textured, often quite gravelly-sandy soils show a very high water infiltration rate and a groundwater level of >3.0 m below the surface. Mostly, the plant available water storage capacity (PAWC) is less 90 mm (Geldmacher 1993).

As expected, intensive and long-term wastewater irrigation (800 to 5,000 (7,000) mm yr^{-1}) causes a considerable accumulation of organic matter in the topsoil (Ahj, upper B horizon, SOM makes up 3 to 70 % of the soils mass). On the other hand, it induces anoxic conditions in the subsoil, forming typical *Cumulic Anthrosols* (Blumenstein et al. 1997, Figure 13). Well-documented, sewage sludge fields in the surrounding of *Berlin* are contaminated by heavy metals from industrial sources. On heavy polluted settling basins the maximum concentrations of cadmium, copper or zinc exceed the national threshold values for a harmless agricultural land use and the reference of uncontaminated soils up to a multiple, sometimes even 2,500 times (Schlenther et al. 1992, Grunewald 1993, Blumenstein 1995, Hoffmann et al. 1995, LUA 2008, Table 5 and 6). Even more, the contamination level is much higher as at other sewage farms in *Germany* due to long-standing irrigation and high portion of industrial wastewater (Table 7).

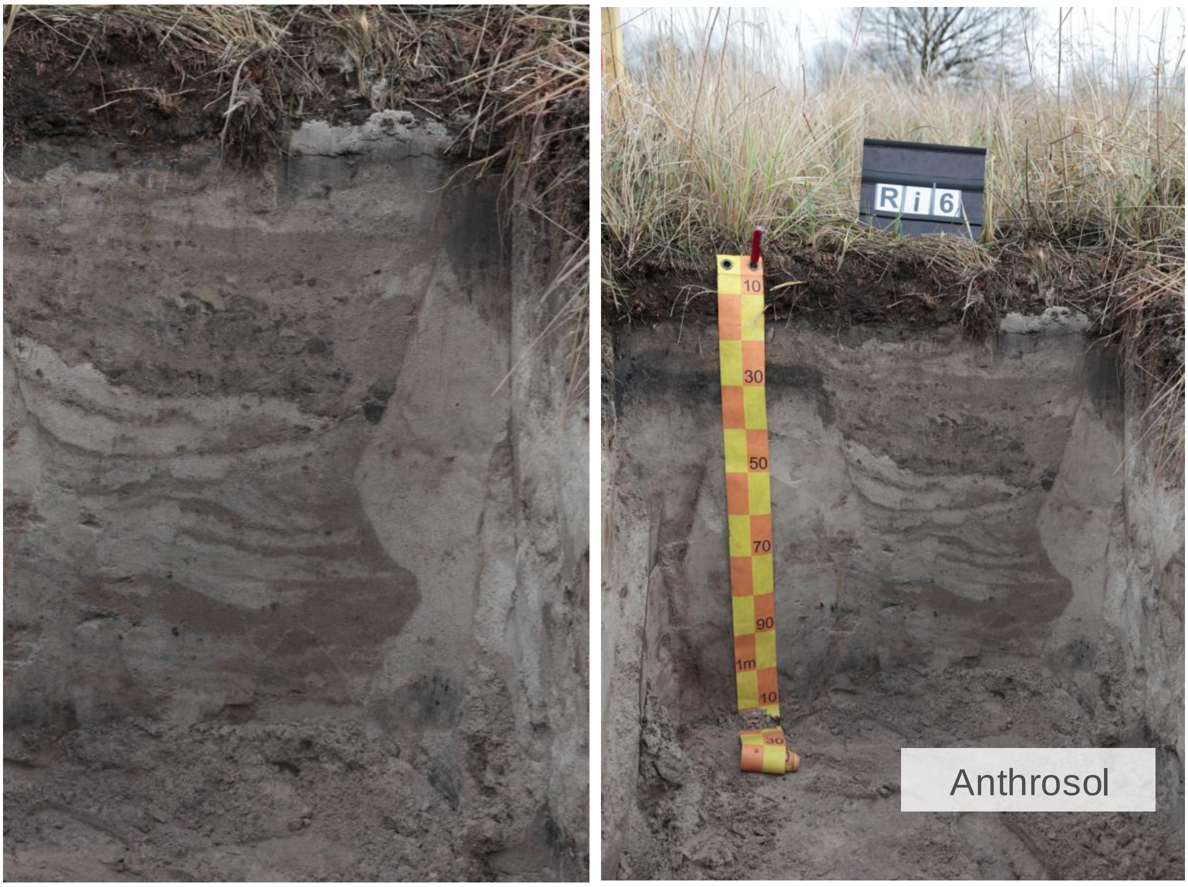

FIGURE 13: ***CUMULIC ANTHROSOL*** **AT SEWAGE FARM** ***COTTBUS-SASPOW*****, WITH THE TYPICAL ACCUMULATION OF ORGANIC MATTER (SOM) IN THE TOPSOIL.**

In general, the organic matter content of the mineral soil corresponds to the concentration of heavy metals (Cu, Zn, Cd, Pb). On such sorption-poor sandy soils the less degradable organic compounds are essential for the sorption capacity.

TABLE 5: HEAVY METAL POLLUTION (HNO_3 EXTRACTION, TOTAL CONTENTS) OF IRRIGATION SITES NEARBY *BERLIN* IN PERCENT OF THE TOTAL IRRIGATION AREA, GRÜN ET AL. (1989)

Element	**no / low contamination**		**medium contamination**		**high contamination**	
	mg kg^{-1}	**area %**	**mg kg^{-1}**	**area %**	**mg kg^{-1}**	**area %**
Cadmium	0.1 - 1.5	26	1.5 - 10	66	10 - 43	8
Copper	8.1 - 90	81	90 - 180	17	180 - 730	2
Nickel	1.4 - 15	79	15 - 25	15	25 - 95	6
Lead	13 - 90	73	90 - 450	27	450 - 1,050	0.4
Zinc	49 - 240	67	240 - 400	23	400 - 1,830	10

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TABLE 6: HEAVY METAL POLLUTION (HNO_3 EXTRACTION, TOTAL CONTENTS) OF IRRIGATION SITES IN THE SOUTH OF *BERLIN* IN PERCENT OF THE TOTAL IRRIGATION AREA, BLUMENSTEIN ET AL. (1997), AVERAGE (ARITHMETIC), MINIMUM - MAXIMUM

Element	Irrigation channel system [1]	Irrigation field / irrigation zones	Separating dams [2]	Sedimentation and mud settling ponds
		mg kg^{-1}		
Cadmium	2.7 0.4 - 6.5	9.8 0.3 - 41	6.6 0.9 - 32	11.9 0.1 - 70
Copper	163 3.0 - 990	108 2.0 - 480	189 26 - 771	447 8.0 - 1,306
Lead	154 8.0 - 428	188 6.0 - 694	224 10 - 800	265 3.0 - 977
Chromium	61 0.1 - 180	33 4.0 - 140	71 12.0 - 285	166 3.0 - 425
Nickel	18.5 16 - 66	38 1.0 - 180	27 4.0 - 130	64 1.0 - 190

[1] the irrigation channels were cleaned regularly, [2] where the excavated material from irrigation channels was deposited

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TABLE 7: HEAVY METAL POLLUTION OF IRRIGATION SITES (ONLY TOPSOIL, MEAN) IN *BERLIN & BRANDENBURG* AS COMPARED TO OTHER SEWAGE FARMS OUTSIDE (*BRAUNSCHWEIG, MÜNSTER, MAGDEBURG* & *FREIBURG*)

Element	*Berlin & Brandenburg*1)	*Braunschweig*2)	*Münster*3)	*Magdeburg*4)	*Freiburg*5)
			mg kg^{-1}		
Cadmium	16	0.8	<0.3	1.0	1.1
Copper	810	n.d.	22	69	35
Lead	2,310	96	61	111	108
Zinc	450	159	178	329	245

1) Aurand et al. (1984), 2) Mühlnickel et al. (1989), 3) Felix-Henningsen & Erber (1992),
4) Meissner et al. (1993), 5) Heinrichsmeyer (1995), n.d. = not determined

Moreover, in part irrigated sites indicate considerable levels of xenobiotics like harmful PAH (polycyclic aromatic hydrocarbon) and PCB (polychlorinated biphenyls) (Kratz 1995). In general, both heavy metals and organic contaminants correlate with the organic substance and therefore accumulate in the topsoil (Renger et al. 1995, Schlenther et al. 1996). The highest concentrations are measured in wastewater and mud settling ponds but also at the inlet of irrigation zones. Already Metz et al. (1990) and Blumenstein (1995) describe a typical spatial and vertical distribution.

Although, contamination is heterogeneous most irrigation fields show quite similar basic characteristics with respect to their suitability for biomass production. However, except to the farms nearby *Berlin* there is only little information available about the situation on site. Moreover, irrigation fields underlie high soil dynamics, especially when aerated again.

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Soil dynamics on disused sewage farms – from excess water to water shortage

From the ecological point of view irrigation fields are artificial, quite unstable systems. By ending of irrigation there is again a rapid change of both hydrological-/chemical and morphological-structural properties (Ginzel & Nützmann 1998, Diehl 2003). At first the end of use as irrigation fields leads to a local ground water level lowering and a deep drying of the sandy substrates. Soil aeration triggers the mineralisation of easily bio-degradable soil organic matter associated with a strong drop of soil pH value. As it is widely known, mobilisation and dislocation of acid-soluble heavy metals and organic complexes increases slightly when the soil pH value is lower than 5.5 (Alloway 2012). This effect is intensified by pH values lower than 4.5. For instance, Herms & Brümmer (1989) name as critical pH values: Cd (<6.5), Cu (<4.5-5.0), Mn (<5.5-6.0), Pb (<5.0) and Zn (<5.0-5.5). At some heavily polluted mud settling ponds it has already a harmful impact on plant growth (Koch & Wilke 1998) and groundwater quality (Nützmann et al. 2000). Besides, a strong leaching of TOC, chloride and sulphate and easily water soluble macronutrients occurs, especially nitrate and ammonium.

Although the vegetation aspect reflects an ongoing soil degradation, the long eutrophic *"history"* of sewage irrigation sites is still visible (Sukopp 1990). Very often there is a heterogeneous ruderal vegetation mosaic of small reeds (*Calamagrostis epigejos*), couch grass (*Elymus* spec.), stringing nettle (*Urtica dioica*) or other tall perennial herb meadows. In addition, when irrigation came to an end, there was an invasion of nitrogen demanding *European* elder (*Sambucus nigra*) still forming small groups of bushes and groves.

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High site heterogeneity makes any growth forecast difficult

Very often former dams separating the single irrigation zones have been levelled (Ritschel & Kratz 2000). Such remodelled areas show up to 1.0 m thick and quite heterogeneous *Cumulic Anthrosols* depending on the specific discharge, variable sedimentation of particles and the degree of substrate redistribution. Other reclamation options are the coverage of heavy polluted sites with excavated earth and other mineral residues, soil replacement or amendment. All the more, the complex situation demands high-resolution information, not only about the contamination level but also the agronomic properties (water holding capacity, nutrient supply, bioavailability of contaminants and potential phytotoxic effects).

To avoid any unforeseen crop failure an individual land preparation is necessary according to the site properties and intended after-use, i.e. soil coverage, amelioration, basic fertilisation and mulching. A key factor for a successful cultivation of crops on former irrigation fields is a crop rotation with quite stress tolerant (heavy metals, dryness), undemanding (in terms of water and nutrient supply) species. Even more important is the consequent crop management, especially weed control due to the strong soil weed seed bank.

Cropping and yield potential on disused sewage irrigation fields

Insufficient database and uncertainties

Although sewage irrigation fields show a considerable pollution the yield potential is comparable to marginal farmland of the region. That means that the sandy soil texture with its low plant available water capacity and poor macronutrient sorption is the growth-limiting resource. Unfortunately, both the database and cropping experience are weak, even more as the site conditions are quite contrasting on a small scale. It follows that the cause-and-effect relationships remain unclear, which make cropping recommendations difficult.

So far only a few current experiences exist from the cultivation of annual bioenergy crops like maize or *Sorghum* or other perennial crops but trees, like mixed *Silphie* (*Silphie perfoliatum*) or *Miscanthus x giganteus*. Due to the absence of resilient information data from conventional agricultural sites can be used by analogy. In particular, data from poor, sandy sites of the surroundings should be considered. As a *"low-input option"* the use of the current grassland vegetation can be contemplated, as well. In this context, a plant-adapted wastewater irrigation leads to a considerable yield increase up to 40 %, depending on the crop (Table 8). However, there are only very few reliable information about the biomass potential of non-food feedstock after stopping irrigation.

TABLE 8: YIELDS ON SEWAGE FARM LAND: NON-IRRIGATED AND WITH A PLANT GROWTH ADAPTED WASTEWATER IRRIGATION REGIME, "*ON-FARM*" TRIAL *BERLIN-MALCHOW*, METZ (1995)

Crop	Yield (Mg ha^{-1} yr^{-1})		Additional yield	
	Non-irrigated	Irrigation	Mg ha^{-1}	kg mm^{-1}
Grasses (*Dactylis*, *Lolium*) (dry matter)	9.5	13.0	3.5	16
Silage maize (dry matter)	6.6	8.6	2.0	15
Potatoes (tuber)	21.8	28.6	6.8	91
Winter rye (grain)	5.2	5.4	0.2	4

Besides the soil texture the cropping potential depends on certain chemical properties, especially the heavy metal contamination. Especially zinc, copper and nickel are phytotoxic at higher concentrations. Already Wilke & Metz (1993) and Metz (1995) found out by pot experiments that in particular maize and some grasses (cocksfoot / *Dactylis glomerata*, darnel / *Lolium* spec.) are quite heavy metal tolerant. On the other hand, rye (*Secale cereale*) and lignocellulosic feedstock like perennial *Miscanthus* (*Miscanthus sinensis or M. x giganteus*) or giant knotweed (*Reynoutria sachalinensis*) prove to be more sensitive to high copper and zinc concentrations in the soil.

First reliable yield information exists for hybrid poplars (*Populus spec.)*, black locust (*Robinia pseudoacacia*) and hybrid willows (*Salix spec.*) (Mollnau & Murach 2013, Koim & Murach 2015). In particular, the *Berliner Stadtgüter GmbH* as major land owner is involved in the cultivation of SRC. Together with several practice partners three locations nearby *Berlin* are managed: *Deutsch-Wusterhausen*, *Wansdorf* and *Schönerlinde*. Moreover, the energy company *RWE* established 300 ha SRC at *Deutsch-Wusterhausen* in 2009 (Schön 2010). However, this quite ambitious project failed a few years later due to changes in the groups strategic orientation and business model. Besides evident management risks, some financial calculations indicate that it is almost impossible to cross the profitability threshold, even in the long term (Feger 2010).

FIGURE 14: ONE YEAR OLD SHORT ROTATION COPPICE WITH POPLAR (CLONE *HYBRIDE 275*) ON A FORMER SEWAGE FARM AT *SCHÖNWALDE-GLIEN*

Due to the high site heterogeneity the increment of the trees is quite different and sometimes very low.

An underestimated obstacle is the comparable low heavy metal tolerance of poplar and willow. On some of the former settlings basins three year old plants show Zn induced leaf chlorosis and growth depressions (Figure 14 and 15), while on others they grew quite satisfactorily (Koim & Murach 2015). Based on scientifically monitored plantations and growing trials only few, more stress-tolerant poplar hybrids are recommended for the cultivation (Table 11).

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FIGURE 15: HYBRID POPLARS WITH GROWTH DEPRESSION AND CHLOROSIS DUE TO HIGH ZINC CONCENTRATIONS IN THE SOIL, ON A FORMER SEWAGE FARM NEARBY *BERLIN*

On the other site, black locust is well-known for its considerable acid and good heavy metal tolerance. However, plantations on sewage farms reveal unexpected die backs in the year after planting, which are mainly caused by fungal attack of *Fusarium spec.* and *Phytophtora* spec. (up to 70 % mortality, Landgraf & Heydeck 2014). These secondary parasites benefit from some predisposing factors, such as late frosts and weed pressure. At least, only very few of the planted 100 ha black locust are developing satisfactorily. Even afforestations fail very often (Schlenther et al. 1996). In addition, Kappel & Japp (2006) report losses due to unprofessional planting with low-grade plant material.

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…calling for conclusions by analogy – yield assessment and profit contribution of marginal land

In fact, remaining sewage sites are municipal land reserve for a prospective, still uncertain use. Most parts of the *"open landscape"* are agricultural sites and abandoned land managed extensively without any commercial motive or need (landscape conservation). In particular, former irrigation fields appear as land *"set-aside"* and permanent pastures. Disused sewage farm can be classified as marginal land although long-term irrigation in the past caused a considerable accumulation of soil organic matter. That means that the average soil quality (maximum value = 100) is less than 23 to 28 yielding points (*"deprived zone"*). Therefore, without additional *EU Single Farm Payments* (SP) as direct subsidy grant to the landowners (cross compliance, environmentally-friendly farming) the profit contribution remains negative for all crops under the current market situation. A more detailed orientation provides Table 9. Over there, Hanff & Lau (2016) are calculating the marginal return for common cereals and oil seeds growing on marginal land in the case study region.

This quite sobering result calls for low-cost and low-input (fertiliser, pesticides, water) management systems, especially feedstock production for bioenergy (firewood, advanced biofuels). However, even undemanding hybrid poplars are currently not profitable without an additional financial support. In other words: regarding the overall poor site conditions for farming, even large-sized, highly mechanised agricultural companies rely on single farm payments to remain competitive and successful on a more and more deregulated marketplace.

TABLE 9: CROP YIELDS (CEREALS, OIL SEEDS AND WOODY BIOMASS) AND CALCULATED PROFIT CONTRIBUTIONS ON A MARGINAL AGRICULTURAL LAND (*"LANDBAUGEBIET IV"*) IN *BERLIN & BRANDENBURG*, ACCORDING TO HANFF & LAU (2016)

Crop	Yield [1] (Mg ha^{-1} yr^{-1})	Profit contribution without *EU Single Payments* (€ ha^{-1} yr^{-1})	Profit contribution with *EU Single Payments* (€ ha^{-1} yr^{-1})
1st generation biofuels			
Winter rape	2.5	98	353
Summer rape	1.1	-215	40
Sunflower	1.7	-300	-45
Linseed	0.7	-256	4
Blue lupine	1.6	-306	-50
Field peas	1.8	-298	-43
2nd generation biofuels [2]			
Winter rye (population varieties)	3.5	-135	121
Winter wheat	3.8	-54	202
Winter barley	3.6	-139	116
Oat	2.7	-99	156
Winter triticale	3.7	-153	102
Hybrid poplar	5.0	-171	84

[1] for cereals and oil seeds: corn yield, in case of SRC leafless aboveground biomass (DM), [2] 2nd generation biofuels: woody biomass and agricultural residues (so-called *"opportunity fuels"*)

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Miscanthus as an option for disused sewage fields?

High-yielding and undemanding *Miscanthus x giganteus* can be used for the biomass production on a wide range of agricultural land (Biertümpfel et al. 2001, Clifton-Brown et al. 2001, Röhricht 2008, Pude 2009,). Among others, De Vries et al. (2014) highlight the water use efficiency, that might be an important advantage in terms of the risk of summer droughts within the case study region.

In *Germany* approx. 2,000 ha of *Miscanthus* are in cultivation with a rising trend (Becker et al. 2014). Due to the fact that no yield data from *Miscanthus* from disused *German* sewage fields were available, three stands of *Miscanthus x giganteus* on common agricultural sites in the *Lusatia* region were investigated in August 2016 within the FORBIO project. Let´s have a closer look on the quite promising results in Table 10: the stalk-biomass ranges from 3.2 Mg DM ha^{-1} yr^{-1} (*Klementinenhof* 2, Plot 2) to 23.5 Mg DM ha^{-1} yr^{-1} (*Klementinenhof 1*, Plot 1) due to the heterogeneous site conditions. In consideration of both, stalk and leave-biomass, the dry matter yield is between 4.5 Mg ha^{-1} yr^{-1} (*Klementinenhof 2*, Plot 1) and even 30.9 Mg ha^{-1} yr^{-1} (*Klementinenhof 1*, Plot 1).

Summing up, *Miscanthus* cultivation (*Miscanthus giganteus*, *Miscanthus sinensis*) is still in the experimental phase. While high-yielding sites in the climatically favoured regions of *(South)Western Germany* show yields of approximately 10 to 25 Mg DM ha^{-1} yr^{-1} after 4 years (Pude 1997, Seidel 2013) in *Brandenburg* 5 to 15 Mg DM ha^{-1} yr^{-1} are cropping reality. In addition, model calculations of de Vries et al. (2014) indicate 10 Mg DM ha^{-1} yr^{-1} as average over a 15 years plantation cycle. Especially severe winters and late frost in spring can cause high losses in first-year plantings. Moreover, *Miscanthus* shows a slow initial growth. Thus, on eutrophic sewage farms the strong weed competition may be a serious problem for plantings from rhizome or micro propagated material.

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TABLE 10: DRY MATTER OF *MISCANTHUS* LEAVES AND STALKS IN DIFFERENT AGED STANDS ON THREE COMMON AGRICULTURAL SITES IN SOUTH *BRANDENBURG*

Site / age	Plot	Compartment	Yield [1)]($\mathrm{Mg\ DM\ ha^{-1}\ yr^{-1}}$)	Yield [2)] ($\mathrm{Mg\ DM\ ha^{-1}\ yr^{-1}}$)
Klementinenhof 1 4 year old stand	1	L	7.4	30.9
		S	23.5	
	2	L	3.3	14.1
		S	10.7	
	3	L	2.4	8.8
		S	6.4	
Klementinenhof 2 2 year old stand	1	L	1.3	4.5
		S	3.2	
	2	L	3.4	12.6
		S	9.2	
	3	L	3.5	13.7
		S	10.2	
Kleinkrausnick 3 year old stand	1	L	5.5	21.7
		S	16.1	
	2	L	5.1	21.9
		S	16.9	
	3	L	4,8	21.0
		S	16.2	

1) mean of two selected plants per plots, 2) sum of mean yield of leaves (L) and stalks (S)

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Establishing fast-growing woody crops on disused irrigation fields

The poor site quality of disused irrigation fields in *Berlin & Brandenburg* calls for extensive forms of subsequent use. As proofed on other disturbed and marginal sites, low input SRC with fast-growing poplar hybrids, willow or black locust are a promising option (Sobioch 2013). However, the first determination of planting success and initial biomass increment is quite sobering. There is a wide range of growth performance, depending on the high soil heterogeneity, variable pollution situation with heavy metals and overall strong weed competition (Koim 2015). First on-farm experiments indicate that at least only a consequent site preparation by tillage (ploughing up of grassland) with an additional herbicide application (pre-emergence treatment) is promising (Beßler & Engels 2012, Koim et al. 2015).

Looking at the necrotic and weak growing trees, the Zn contents in the root zone are much higher as compared to sprouts free of symptoms. As well an additional analysis of the soil solution, fine roots and leafs reveal an oversupply of Zn, Cd and Cu (Mollnau & Murach 2013). Moreover, Koim & Murach (2015) point out differences in the growth and the survival rate of poplars (clone *Max 1*) and willows (clone *Tordis*) (Table 11). However, the remarkable 13 Mg ha^{-1} yr^{-1} of *Max 1* established with 80 cm rods may be an exception due to the exemplary management of a scientific growing trial.

Finally, a visual inspection of the plantings reveals that damages caused by game (especially roe deer) should be taken seriously. In fact, irrigation fields are smooth, small-structured habitats with a considerable biodiversity and good food supply (high protein shrubs) over the year (Sukopp 1990).

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TABLE 11: GROWTH CHARACTERISTICS OF SHORT ROTATION POPLARS AND WILLOWS ON A FORMER SEWAGE IRRIGATION FIELD NEARBY *SCHÖNWALDE-GLIEN/WANSDORF* (KOIM & MURACH 2015)

Species	Clone	Type and length of planting material	Mean annual increment (Mg DM $ha^{-1}yr^{-1}$) 1)	survival rate (%)
Populus spec.	Max 1	cuttings (20 cm)	0.4 - 6.4	17 - 78
Populus spec.	Max 1	rods (80 cm)	12.9	96
Salix spec.	Tordis	rods (80 cm)	8.4	94

1) leafless aboveground biomass (DM)

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Cross-cutting issues

Suitable crops for bioremediation

A most desirable cross-cutting issue for non-food feedstock production on disused sewage farms is the so-called phytoextraction of heavy metals with the subsequent removal of harmful substances from the recovery process (exclusion). Therefore, worldwide more than 400 special *"hyper-accumulators"* are identified, comprising a wide range of plant families and genus (Reeves & Baker 2000, McIntyre 2001). In common these species take up and translocate metal contaminants (Zn, Ni, Cd and Pb) via the roots into the aboveground biomass far beyond the physiological optimum and at level 100-150-fold greater than common plants without yield reduction (Brooks 1987, Chaney et al. 2007, Paz-Ferreiro et al. 2014). For example, stinkweed (*Thlaspi caerulescens*) is able to concentrate 8,000 mg Zn kg^{-1} DM, that are 43 kg ha^{-1} in one vegetation period. Other cruciferous plants (*Brassicaceae*) but also stonecrop (*Alyssum* species) are classified as very efficient Ni accumulators with shoot contents of >1 % of dry matter biomass (Brooks et al. 1979, Baker & Brooks 1989).

Unfortunately, many of these species are adapted to dry sites. They have a small ecological amplitude, low biomass production and are only less competitive (Salt et al. 1995). Furthermore, they can accumulate one or two pollutants very efficiently, and at least there are only 25 species left accumulating three or even more pollutants (McIntyre 2003). In the study region *Berlin & Brandenburg* the following species could be promising for bioremediation (Table 12):

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TABLE 12: PROMISING PLANT SPECIES FOR BIOREMEDIATION OF FORMER IRRIGATION FIELDS; FOLLOWING RASKIN & ENSLEY (2000), TSAO (2003) AND MERKL (2005)

Procedure	Substrate / Medium	Pollutant	Plant species
Phytoextraction	soil, sediments, dredging, sludge	Cd, Co, Cr, Cu, Hg, Mn, Mo, Ni, Pb, Zn	sunflower, lucerne, *Sachalin* knotweed, brown mustard, stonecrop, stinkweed, hybrid poplar
Phytostabilisation and phytostimulation	soil, sediments, dredging, sludge	As, Cd, Cr, Hg, Pb, Zn	brown mustard, hybrid poplar, willow, grasses (cocksfoot, darnel)
Phyto-/ Rhizodegradation	soil, sediments, dredging, sludge	organic contam. (MKW, PHK, CHC, PCB)	lucerne, hybrid poplar, willow, grasses, bulrush
Phyto-volatilisation	soil, sediments, dredging, sludge	organic xenobiotics	willow, poplar, lucerne
Hydraulic control	seepage and ground water	organic contam. and heavy metals	hybrid poplar, willow, black locust
Vegetative cover system	soil, sediments, dredging, sludge	organic contam. and heavy metals	hybrid poplar, willow, black locust, grasses

Description of procedure terms (according to Merkl 2005 and Paz-Ferreiro et al. 2014):

phytoextraction = uptake of pollutants via plant roots and subsequent accumulation in the harvestable biomass, i.e. shoots

phytostabilisation = limiting the mobility of polluting substances in the soil by binding at roots and soil organic matter, prevention of migration or immobilization

phytostimulation = microbial degradation of pollutants is stimulated by plants (release of exudates, improvement of soil structure and aeration)

phyto-/rhizodegradation = degradation of organic xenobiotics in the rhizosphere by plant enzymes and microorganisms, through biological metabolism

phytovolatilisation = conversion of pollutants to a volatile form and release in the atmosphere

hydraulic control = in the waterlogged soil plant transpiration causes a water flow towards the roots (hydraulic suction)

vegetative cover system = a dense and water consuming water vegetation minimizes the seepage water formation and the leaching of pollutants

Therefore, especially on less contaminated sites the cultivation of fast-growing but undemanding annual and perennial agricultural crops with a broad accumulation spectrum are of increasing interest (Haensler 2003, Unterbrunner et al. 2006). Conventional bio-energy crops compensate a lower uptake and translocation rate as compared to accumulators with a manifold higher biomass increment (Baker et al. 1994, Morel et al 2006). These include brown mustard (*Brassica juncea*), lucerne (*Medicago sativa*), tobacco (*Nicotiana* spec.), maize (*Zea mays*), miscanthus (*Miscanthus sinensis, x giganteus*), amaranth (*Amaranthus* spec.) and sunflower (*Helianthus annuus*). But also deep rooting lucerne has a considerable potential for uptake and volatilisation of human toxic hydrocarbons (Ferro et al. 1997, Rice et al. 1997). Pradhan et al. (1998) reported even a reduction of initial PAHs content by 57 % within half a year.

However and as previously discussed, on disused sewage farms the low water storage capacity and lack of some micronutrients is crop growth limiting. So it is likely that an appropriate irrigation increases biomass production and the decontamination. This applies to all fast growing annual crops, like maize, *Shorgum*, tobacco or lucerne, beyond the economic considerations (Table 14). Therefore, Unterbrunner et al. (2006) recommend for summer dry regions in general a demand-based irrigation of crops to support the withdrawal of contaminants. The plant-physiological optimal soil moisture content in the growth period is about 40 to 100 % of the soil water holding capacity (field water capacity, FC).

Already Metz & Wilke (1993) performed some first pot experiments with different heavy metal contents screening the estimated biomass production and decontamination effects of silage maize (*Zea mays*), winter rye (*Secale cereale*), *Miscanthus* (*Miscanthus sinensis*), and invading *Sachalin* knotweed (*Reynoutria sachalinensis*). In general, the highest transfer rates from soil to plant can be expected on less and medium polluted sewage farms, which comprise 90 % of the area. Thereby, the cadmium removal from the topsoil into the biomass makes up to 1 - 6 % as compared to the initial soil content in one cropping period. As Table 13 points out, silage maize shows the highest biomass production on both less and highly contaminated sites.

And regarding the accumulation silage maize but also *Sachalin* knotweed as well are convincing. Latter is an invading wild plant, but the risk may be controllable because *Reynoutria sachalinensis* distributes itself by rhizome growth, not by seeds. Perennial knotweed is obviously good site adapted and stress tolerant. As a self-reproducing permanent and sustainable crop it offers perspectives for a resource efficient, more advanced biofuel production.

TABLE 13: RANKING OF SOME PROMISING CROPS FOR FEEDSTOCK PRODUCTION ON DISUSED IRRIGATION FIELDS WITH RESPECT TO THEIR BIOMASS PRODUCTION AND CADMIUM TRANSFER (EASY BIOAVAILABLE REFERENCE ELEMENT WITH HIGH HUMAN TOXICITY EFFECTS), ACCORDING TO POT EXPERIMENTS BY METZ & WILKE (1993)

Criterion	Less contaminated (Cd, Cu, Zn)

Biomass production	Silage maize > *Miscanthus* > *Sachalin* knotweed > Winter rye
Cd concentration in plant	*Sachalin* knotweed > Winter rye > Silage maize > *Miscanthus*
Decontamination effect	*Sachalin* knotweed > Silage maize > *Miscanthus* > Winter rye
Criterion	**Heavily polluted (Cd, Cu, Zn)**
Biomass production	Silage maize > *Sachalin* knotweed > *Miscanthus* > Winter rye
Cd concentration in plant	*Sachalin* knotweed > Winter rye > Silage maize > *Miscanthus*
Decontamination effect	Silage maize = *Sachalin* knotweed > *Miscanthus* = Winter rye

TABLE 14: SUITABLE ENERGY CROPS FOR PHYTOREMEDIATION OF FORMER IRRIGATION FIELDS IN THE CASE STUDY REGION *BERLIN & BRANDENBURG*; DATA PROVIDED BY SAUER ET AL. (2013), ZIARATI & ALAEDINI (2014) AND HANFF & LAU (2016)

Plant species	**Suitability for phytoremediation**	**Utilisation, expected yield (aboveground biomass)**
Amarant	very high heavy metal accumulation in aboveground biomass	suitable energy crop, however, less known about the specific energy yield, as catch crop[1)] approx. 8 Mg DM ha^{-1} yr^{-1}
Miscanthus	medium to high heavy metal accumulation in aboveground biomass	very suitable perennial energy crop for marginal land (energetic use, biofuels), yield after 3 years about 10 to 25 Mg DM ha^{-1} yr^{-1}
Sunflower	medium to high heavy metal accumulation in aboveground biomass	suitable energy crop on marginally productive land, yield between 10 to 20 Mg DM ha^{-1} yr^{-1}
Mixed *Silphie*	less heavy metal accumulation in aboveground biomass than before	suitable perennial energy crop on marginal land, yield after 3 years about 10 to 25 Mg DM ha^{-1} yr^{-1}
Sorghum, *Sudan* grass and switchgrass	unfortunately, no reliable information on decontamination performance	well established, quite draft tolerant cropping alternatives to maize on marginal land, with a wide geographical range and high energy content, yield from 10 to 15 Mg DM ha^{-1} yr^{-1}

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1) catch crop grows between successive planting of main crops

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An innovative approach: woody biomass for decontamination and hydraulic control of sewage irrigation fields

A new approach for *in-situ* pollutant clean-up is emerging in the scientific community: the cultivation of fast-growing woody biomass as a long-term way of on-site soil remediation. Especially willow and hybrid poplar seem to be quite promising (Sauer et al. 2013): following Unterbrunner et al. (2006), some selected clones accumulate up to 400 mg kg^{-1} Cd and 5,000 mg kg^{-1} Zn in the harvested aboveground biomass. Even more, deep rooting hybrid poplars contribute to a significant phytodegradation of organic pollutants like dioxin (PCDD, PCDF), PCBs and PAHs (Gordon et al. 1997, Tsao 2003). However, still grasses and herbaceous plants like lucerne, which are naturally pre-adapted to higher uptake rates, are preferred (Pradhan et al. 1998, Banks et al. 2003, Ward & Singh 2004).

On the other hand, dense permanent stockings show a much higher biomass transpiration as compared to annual plants minimising the seepage water formation and leaching of contaminants (hydraulic control, vegetative cover system (Hüttl & Semmel 1995). Lamersdorf & Schulte-Bisping (2010) simulated the water budget of two quite typical short rotation coppices (SRC) on marginal land in the case study region. As a result, the actual evapotranspiration during the vegetation period is 2.5 to 3.0 mm d^{-1}, which is about 50 to 65 % of annual precipitation. During dry years with less than 500 mm rainfall deep percolation and ground water recharge come to standstill.

In contrast, the water removal of nearby agricultural sites is just below 40 % of annual rainfall. However, the water recharge of SRC is higher than the one of closed common oak (*Quercus petraea*) forests (29 %) and *Scots* pine (*Pinus sylvestris*) stands (22 %) in the region (Knoche et al. 2012b). But regarding the climatic conditions of the region, it can be concluded, that a water consuming woody biomass is an effective procedure for safeguarding environmentally hazardous sewage sites, especially on soils with a high hydraulic conductivity.

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Land conservation through utilisation – grassland to bioenergy?

Frequently, small structured sewage irrigation fields show a considerable ecological biodiversity. And especially when they fall into declared protected landscapes and nature reserves there are several limitations in management, i.e. only grassland use, no herbicide applications, prohibition of grassland conversion into arable land. This *"set aside"* land is managed extensively, with a special focus on landscape maintenance, in particular by mowing of meadows, sometimes even grazing subjected to certain obligations (e.g. stocking density, Hasch 2014). On the other hand, a cropping of high-yielding energy crops needs a ploughing up, basic soil amelioration, regular fertilisation and plant protection measures.

It is questionable, if such an intensification is accepted by the responsible nature conservation of the districts and under what additional conditions. This raises the question whether a utilisation of the green waste makes sense for feedstock production. The dominant vegetation is commonly sub cosmopolitan (undemanding, quite stress-tolerant perennial) and rhizomatous grasses (Sukopp 1990). The dominant *Poaceae* are wood small-reed (*Calamgrostis epigeios*), smooth brome (*Bromus inermis*), couch grass (*Elymus* spec.) and meadow grass (*Poa pratensis*) quite typical for semi-dry grasslands with little feed value. They are flood, cold and heat resistant, but preferring warm and dry conditions and nutrient-rich soils. Added to these grasses are some nitrophilous and base tolerant herbs, in particular competing stinging nettle (*Urtica dioica*).

In July 2016 a one-time, orienting biomass determination was carried out on the sewage irrigation fields at *Cottbus-Saspow* and *Finsterwalde* in *South-Eastern Brandenburg* (FORBIO 2016). Given in Table 15 the detected aboveground biomass ranges from 1.5 to 3.7 Mg DM ha^{-1} yr^{-1}, for one cutting just before ripening of the grasses. The differentiating yields are illustrating the small-scale soil heterogeneity of irrigation fields (Metz et al. 1990, Blumenstein 1995). The data are comparable to other semi-natural, not NPK-fertilised and water limited grassland formations in *Germany*. For example, Schmidt (2013) mentions about 2.0 Mg DM ha^{-1} yr^{-1} (like litter meadow, one and two cuttings). With a sufficient water supply 5.5 to 9.0 Mg DM ha^{-1} yr^{-1} (sedge reed) or even 9.5 to 12.0 Mg DM ha^{-1} yr^{-1} (reed grassland) are possible. Again these biomass yields are similar to intensively managed forage grass on intact sewage farms nearby *Berlin-Malchow*. Over there, the yield potential was ranging from 9.5 Mg DM ha^{-1} yr^{-1} (non-irrigated) to 13.0 Mg DM ha^{-1} yr^{-1} (irrigated) as already reported twenty years ago by Metz (1995).

Unfortunately, up to now there are only few records about the management costs of such ruderal sites and the marketing of grass cutting. According to Schmidt (2013) the provision costs are high, but vary in a wide range from approx. 100/200 to 500 € Mg^{-1} DM (one cutting). This calls for more systematic investigations with a focus on cutting date, number of cuttings, additional NPK-fertilisation, processing of cuttings, energetic yield and further material utilisation by biorefining. The basic idea is, to mobilize the unused biomass of sewage irrigation fields, quasi as a by-product of necessary landscape conservation measures to generate a profit contribution margin (PC) at least. In addition, other *"green wastes"* from river and road maintenance offer another potential still hardly used, instead of a costly disposal. The final question is, if there is a real earning potential for agriculture enterprises or agricultural service providers in the region?

Finally, at *Cottbus-Saspow* a special (energy) herb mixture and the seeding of forage *Shorgum* are tested now - both for landscape maintenance, energy purposes and decontamination. Initial results are promising: after ploughing up the grassland and a single seedbed preparation the biomass yield amounts between 2.7 and 3.1 Mg DM ha^{-1} yr^{-1} (herbs) and even 4.5 to 7.9 Mg DM ha^{-1} yr^{-1} (*Sorghum*, FORBIO 2016). Thereby, it has to be taken into account that such a low-input cropping system requires no liming, fertilisation or plant protection at the beginning. Moreover, the vegetation period 2016 is characterised by a strong water-deficit in late summer and early ripening of the crops. Thus, a consistent and permanent arable farming leads to expect considerable higher yields and less production risks under average weather conditions.

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TABLE 15: ABOVEGROUND BIOMASS OF THE SEMI-NATURAL VEGETATION AT THE DISUSED SEWAGE IRRIGATION FIELDS *COTTBUS-SASPOW* AND *FINSTERWALDE*

Dominant vegetation	Yield / one cutting (Mg FW ha^{-1} yr^{-1})	Yield / one cutting (Mg DM ha^{-1} yr^{-1})	Dry matter (% by weight)
Sewage irrigation fields *"Cottbus-Saspow"* (19 ha)			
Smooth brome (*Bromus inermis*)	7.9	1.9	24.3
	9.2	2.8	30.9
	11.7	3.3	27.9
Herb mixture	6.7 - 7.9	2.7 - 3.1 (Ø 2.9)	37.6 - 40.6
Forage *Sorghum*	16.6 - 25.8	4.5 - 7.9 (Ø 6.6)	27.4 - 32.0
Sewage irrigation fields *"Finsterwalde"* (20 ha)			
Wood small-reed (*Calamagrostis epigejos*)	4.6	2.8	61.9
Smooth brome (*Bromus inermis*)	4.9	2.9	58.2
Reed canary grass (*Phalaris arundinacea*)	6.5	3.7	56.3
	2.3	1.5	66.3

one cutting before ripening in July 2016, test plots 10-50 m^2 (FORBIO 2016), harvest of herbs and *Shorgum* in late September 2016

Conclusions

- Not surprisingly land use concepts and management strategies on disused sewage irrigation fields focus on risk prevention concerning the undesirable remobilisation of accumulated heavy metals and organic contaminants. Main points of safeguard are technological, i.e. immobilisation of pollutants by amelioration or application of binders, water logging, surface sealing or soil coverage. The consequence is that many agronomic aspects were not sufficiently considered. There is a major lack of information concerning the biomass production in abandoned sewage farms, i.e. cultivability, cropping system, yield estimates, planting risks and economic feasibility. All the more, these agronomical uncertainties call for basic field trials. Because of the unique soil properties and dynamics any conclusion by analogy of nearby cropland area under regular, quite intensive management is little meaningful.

- From the ecological viewpoint a permanent, habitat-forming biomass production is desirable, in particular of low-input, perennial and self-regenerating agricultural feedstock. But at the moment the yield expectation on marginal irrigation fields is not sufficient or unsteady for a promising investment. However, the intended *in situ* phytoremediation is a desirable cross-cutting effect making sense in terms of hazard prevention, especially on heavy metal polluted sites.

- Finally, the spatial distribution of potential non-food cropping sites on disused irrigation fields calls for smaller, local processing facilities near to the farms or individual on-farm processing solutions, with a manageable feedstock supply and feeding land area. Below the line, it can be concluded that other marginal agricultural land and ligno-cellulosic residues from forestry provide a more substantial opportunity and easier available raw material source.

- The available potential area for the cultivation of energy crops on former sewage irrigation fields in the case study region *Berlin* & *Brandenburg* is about 1,100 ha to 3,900 ha. This area size potential is calculated without the consideration of ecological, economic and political restrictions and barriers. Most promising energy crops with acceptable yields are *Sorghum*/*Sudan* grass, *Miscanthus*, mixed *Silphie* and poplar hybrids (see Table 16 to 18).

TABLE 16: SUMMARY OF GROWN AND CULTIVABLE ENERGY CROPS ON DISUSED SEWAGE IRRIGATION FIELDS - *"TRAFFIC LIGHT SYSTEM"* IN TERMS OF CULTIVABILITY, PART I (ANNUAL CROPS)

"Traffic light"	Plant species / genus	Biomass yield (Mg DM ha^{-1} yr^{-1})	Reference	Comments on usage, experience and cultivation
Annual crops				
🟩	Forage *Sorghum* *(Sorghum bicolor)* *Sudan* grass *(Sorghum sudanense)*	3 - 16 (9.5) 5 - 8 8 -17	M1 GT M1	in practice on common agricultural land in *Berlin & Brandenburg*, a first, quite promising experience provides a cultivation test on a disused sewage irrigation field, even for the summer dry year 2016
🟨	Silage maize (*Zea mays*)	13 - 21 (17)	M1	there are numerous ensured and actual results for the cropping potential on marginal agricultural land in *Berlin & Brandenburg*, but no data for disused sewage irrigation fields available, the low plant available water capacity on the sandy, loose and well-drained soils might be growth limiting
	Winter rye (*Secale cereale*)	5 - 7 (6)	M1	no cropping experiments on disused irrigation fields, however, main crop in the cereal crop rotation on marginal agricultural land with a convincing crop safety

Reference:

M1 = on-farm cultivation on marginal soils in *Berlin & Brandenburg*, FNR (2012), Hanff & Lau (2016)

M2 = on-farm cultivation on marginal to medium quality soils in *Berlin & Brandenburg* - investigations in two stands in South *Brandenburg* (*Lusatia*), FORBIO (2016)

SF1 = on-farm cultivation on disused sewage irrigation fields nearby *Berlin* (*Ragow, Wansdorf*), Mollnau & Murach (2013), Koim & Murach (2015), Koim et al. (2015)

SF2 = on-farm cultivation on disused sewage fields - investigations at two sites in South *Brandenburg*, FORBIO (2016)

GT = growing trial on a disused sewage field, without additional irrigation, nearby *Cottbus*, FORBIO (2016)

PE = pot experiment, Metz & Wilke (1993)

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TABLE 17: SUMMARY OF GROWN AND CULTIVABLE ENERGY CROPS ON DISUSED SEWAGE IRRIGATION FIELDS - *"TRAFFIC LIGHT SYSTEM"* IN TERMS OF CULTIVABILITY, PART II (PERENNIAL CROPS)

"*Traffic light*"	Plant species / genus	Biomass yield (Mg DM ha-1 yr-1)	Reference	Comments on usage, experience and cultivation
Perennial crops				
🟩	*Miscanthus* (*Miscanthus x giganteus*)	5 - 25 (18)	M2	unfortunately no cultivation on disused sewage irrigation fields, but promising to be tested due to the exceptional biomass production on otherwise low-yielding agricultural soils in the case study region
	Mixed Silphie (*Silphium perfoliatum*)	13 - 18 (15.5)	M1	negligible cultivation experiences in *Berlin & Brandenburg* and no growing on disused sewage fields so far, but promising to be tested due to the high biomass production elsewhere in *Germany*
🟨	*Sachalin* knotweed (*Reynoutria sachalinensis*)	8 - 17 (12.5)	PE	over here only first orienting pot experiments, but a quite vital and land spreading neophyte, convincing in first systematic growing trials in the *Czech Republic*
	Permanent or temporary grassland	2 - 4 (3)	M1, SF1, SF2	emanated from natural succession, extensive management for landscape conservation with 1 to 2 cuts per year, only few cultivation data from disused sewage irrigation fields, but comparable to extensive used meadow on marginal water limited pasture of the region

TABLE 18: SUMMARY OF GROWN AND CULTIVABLE ENERGY CROPS ON DISUSED SEWAGE IRRIGATION FIELDS - *"TRAFFIC LIGHT SYSTEM"* IN TERMS OF CULTIVABILITY, PART III (WOODY BIOMASS)

"*Traffic light*"	Plant species / genus	Biomass yield (Mg DM ha-1 yr-1)	Reference	Comments on usage, experience and cultivation

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Woody biomass

🟨	Poplar hybrids (*Populus x spec.*)	0.1 - 12.9 (6.5)	M1, SF1	experiences with cultivation in field trials and SRC on disused sewage irrigation field, some encouraging results, but for a good growth site preparation and weed control needs to be done consequently, problems with heavy metal (Zn) induced micronutrient deficits (Fe)
	Willow hybrids (*Salix x spec.*)	<0.1 - 8.4 (4.2)	SF1	only few experiences with trials on disused sewage field available, less promising results in the first rotation period, site preparation and weed control needs to be done intensively, hardly predictable problems with nutrient deficits and/or heavy metal phytotoxicity, considerable game damages (deer)
🟥	Black locust (*Robinia pseudoacacia*)	0.01	SF1	few published data with overall insufficient results, in the establishment phase severe problems with nutrient deficits, weed competition and fungal attack (*Fusarium* spec., *Phomopsis* spec.), plant-losses up to 70 % in the first three years after planting

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FOSTERING SUSTAINABLE FEEDSTOCK PRODUCTION FOR ADVANCED BIOFUELS ON UNDERUTILISED LAND IN EUROPE

AGRONOMIC FEASIBILITY

PART 2 - CASE STUDY ACTIVITIES ON RECLAMATION SITES IN THE EASTERN GERMAN LIGNITE DISTRICT (LUSATIA)

Contents

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List of abbreviations

AC	*ante Christum* (before Christ)
ACS	alley-cropping system
AFS	agroforestry system
a.s.l.	above sea level
BD	soil bulk density
$CaCO_3$	calcium carbonate
$CaMg(CO_3)_2$	dolomite
CaO	calcium oxide
CAP	EU common agricultural policy
CE	cereal equivalent
C_t	carbon (total)
DM	dry matter
etc.	*et cetera*
EU	European Union
€	euro
FeS_2	ferric sulphide
FIB e.V.	Forschungsinstitut für Bergbaufolgelandschaften e.V.
FORBIO	field experiments and investigations within FORBIO project
g	gram
GAP	good agricultural practices
ha	hectare
i.e.	*id est* (that means)
K	potassium
km^2	square kilometre
m	meter
m^2	square meter
Mg	megagram (= tonne, 1,000 kg)
mg	milligram
mm	millimetre
N	nitrogen
P	phosphorous

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PAWC	plant available water storage capacity of the soil
PC	profit contribution (margin)
pH	pH value
S	sulphur
SOM	soil organic matter
SRC	short-rotation coppice
SQR	soil quality rating index
SRF	short-rotation forestry
VAT	value-added tax
vs.	versus
yr	year(s)
ºC	degree Celsius
%	percentage
Ø	average

Landscape characteristics – geomorphology and climate

The *Eastern German* (*Lusatian)* coal mining area is situated within the transition zone of the *Northeast German Lowlands* and east *Saxonian Hill and Mountainous Country* between the rivers *Elbe* and *Neiße* (Figure 1 and 2). *Quaternary* overburden layers of the *Saale* glacial period with an average thickness of 10 to 50 m contour the landscape, covering *Tertiary* (*Miocene*) facies - in most cases carboniferous and sulphuric acid basin sediments (Table 1). The so-called *"Lausitzer Grenzwall"* end moraine (*Saale III*) is the dominant topographic element, it rises about 50 meters over the surrounding ground moraine surfaces and plateaus (Großer 1998).

Glacial and fluvial sands, dune sands, gravel and loam are soil-forming elements in the landscape. Sandy brown earths, sandy podzols and hydromorphic soils in the glacial valleys dominate among the common soil types. According to the overall poor plant available water storage capacity (PAWC) and nutrient supply, the average yield potential is quite low to moderate. Thus about 60 % of the countryside are covered with undemanding forests. Three quarters of woodland were established with artificially regenerated, less structured Scots pine (*Pinus sylvestris* L.) plantations.

In terms of geographical climate, the study area belongs to the pseudo maritime temperate *"Lusatian climate"* (Kopp & Schwanecke 1994). Summarising, the regional climatic situation can be described as moderate dry to dry lowland climate. In detail: the annual average temperature amounts to 8.0 - 8.5 °C and the monthly mean temperature amplitude is 19 °C. Average precipitation ranges between 580 and 660 mm yr^{-1} with half of the rainfall in the vegetation period. However, the climatic water balance in the growth period is strongly negative (<-150 mm).

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TABLE 1: A SHORT LANDSCAPE CHARACTERISATION OF THE *EASTERN GERMAN LIGNITE DISTRICT* (*LUSATIA*)

Main landscape / Natural region	- *Lusatian Lowland* (90-200 m a.s.l.) - landscape-formative: sediments of the *Lusatian* glacial period (*Saale II* and *III*, 304,000 to 127,000 yr AC), covering lignite bearing *Tertiary* (*Upper* and *Middle Miocene*) strata (approx. 23 to 2,580 mio. yr ago)
Regional Climate	- pseudo maritime temperate *"Lusatian climate"* - mean annual temperature: 8.0 to 8.5 °C - annual amplitude of mean month temperature: 19.0 to 19.5 °C - average precipitation: 550 to 650 mm yr^{-1} (50 % of rainfall in vegetation period from April-September)
Site conditions	- *Quaternary* glacial and fluvial sands, dune sands, gravel and loam with low to medium yield potential - sandy brown earths, sandy podzols, hydromorphic soils
Potential natural vegetation	- Scots pine - sessile/common oak forests - pure Scots pine forests with common birch - mixed oak-lime-beech-forests with some valuable broadleaves - alder-ash swamp forests
Agricultural land use	- arable cropping, dry-land farming with a focus on cereal production - forage cropping with grass-legume-mixtures - extensive pasture farming

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Eastern German Lignite District – area statistics of reclaimed land

With 180 million tons mined lignite *Germany* is still and by far the leading producer worldwide. Thereof 1/3 fall upon the *Lusatia Lignite District* (Debriv 2016). Unquestionable, surface mining is the economic driving force in South *Brandenburg* and North-East *Saxony*. Since the beginning of the 20th century the lignite industry has turned the traditional rural region in a *"man-made landscape"*, with its very specific site conditions and environmental problems (Hüttl et al. 2000, Katzur & Böcker 2010, Figure 3). Up to now, the total devastated area comprises approximately 900 square kilometres, which takes half of the nationwide reclaimed area. Moreover, there are additional 300 km^2 approved for mining in the next decades (Statistik der Kohlenwirtschaft e.V. 2014, Table 2). In addition, there is a wide-ranging impact on the groundwater table leading to a considerable decline of agronomic productivity.

However, about 550 km^2 (61 %) of the reclaimed land are already restored successfully - with registered 10,000 ha farmland and 30,000 ha mixed forests. That is 0.75 % of the agricultural land in *Berlin & Brandenburg* and 2.7 % for the forest area. Summing up, the *Eastern German Lignite District* is the largest artificial landscape in *Central Europe*, and still there are 32,000 ha under management of the mining and reclamation companies (working zone), in reshape or looking for an adequate after-use (Table 2). About 6,900 ha of the working zone are under reclamation; thereof an area of 1,858 ha will be used as agricultural land (VEM 2016). In combination with the agricultural land in already reclaimed area (9,937 ha), there is an area potential for energy crops of about 11,800 ha.

The major target of mine restoration is the compensation of the environmental impact by designing multifunctional post-mining landscapes in accordance with the presetting of regional planning (*Federal Mining Act,* BBergG 1980, *Lignite and Land Recultivation Act*, RegBkPlG 2002). The re-vitalisation is an ongoing process meets a variety of requirements ranging from the re-establishment of functioning ecosystems through reclamation, nature preservation areas and water bodies to public infrastructure (Hüttl 2001). Nevertheless, the multi-stage planning procedure is under public participation, and the landscape of the future is still discussed controversially (Gräbe 2010, Krümmelbein et al. 2012).

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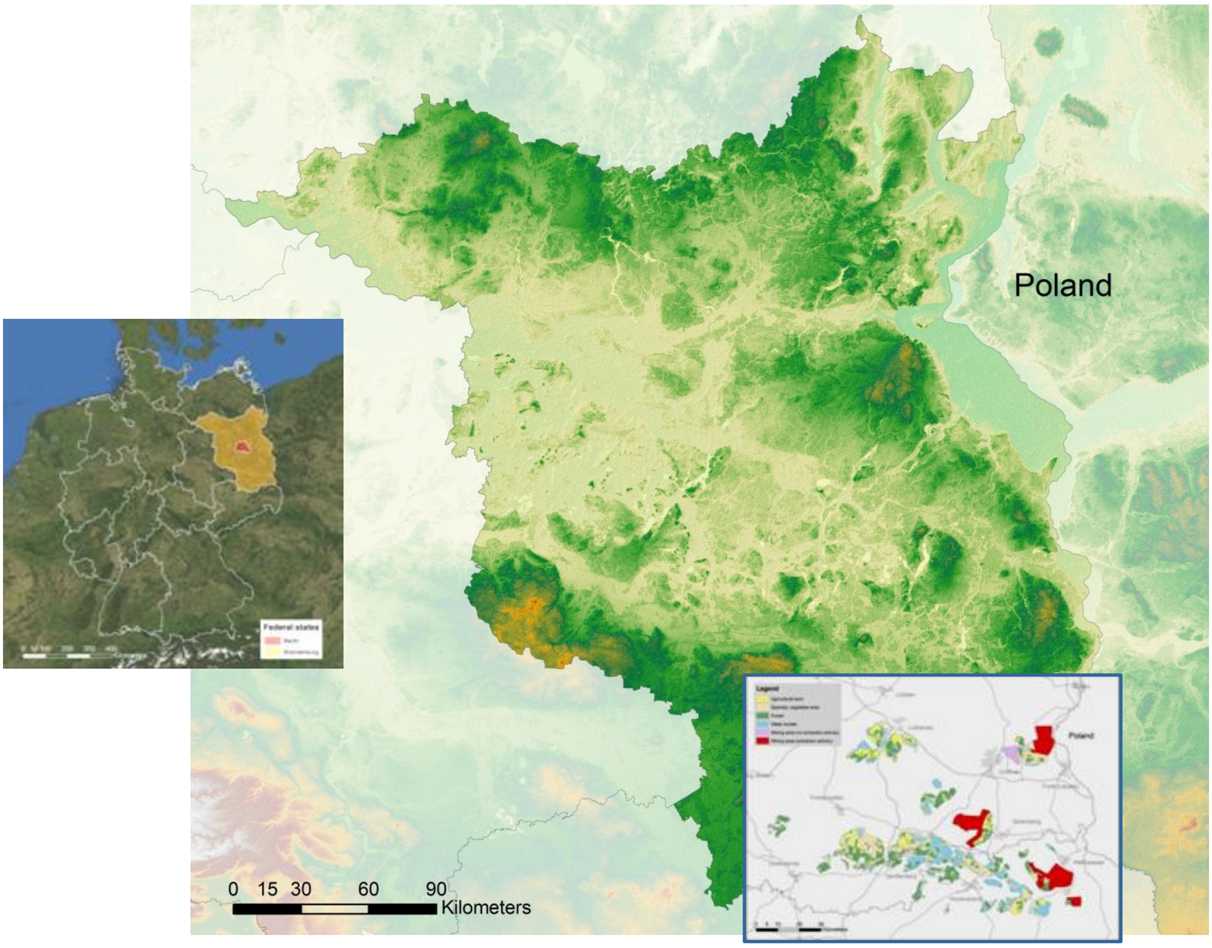

FIGURE 1: LOCATION OF THE *EASTERN GERMAN LIGNITE DISTRICT* IN THE SOUTH-EAST OF *BRANDENBURG* AND NORTH-EAST *SAXONY*

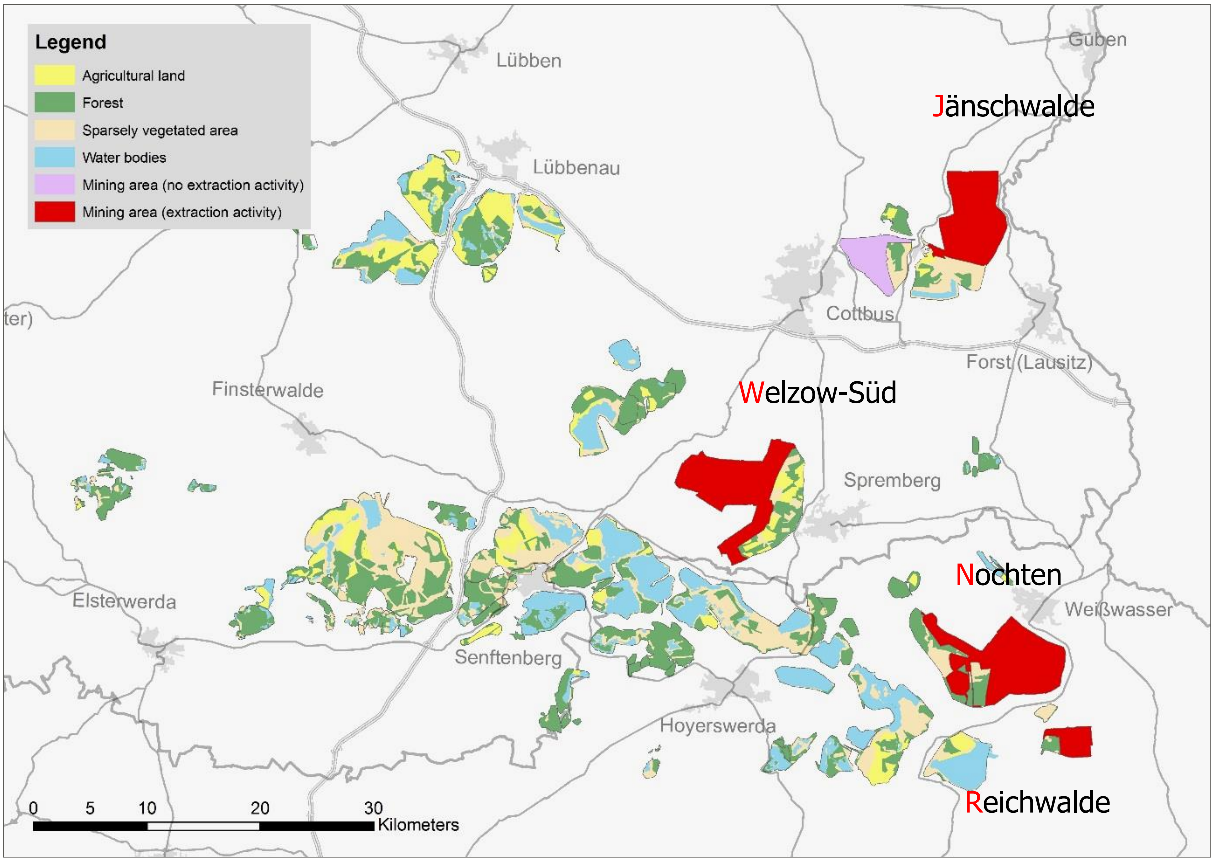

FIGURE 2: OVERVIEW MAP OF THE *EASTERN GERMAN LIGNITE DISTRICT* WITH RECLAMATION SITES AND THE FOUR ACTIVE OPEN-CAST MINES *WELZOW-SÜD, JÄNSCHWALDE, NOCHTEN* AND *REICHWALDE*

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691846.

TABLE 2: LAND DEVASTATION BY LIGNITE OPENCAST MINING AND RECLAMATION AREA IN *GERMANY* UP TO 2014 IN HECTARES, ACCORDING TO STATISTIK DER KOHLENWIRTSCHAFT E.V. (2014)

Land use	***Germany* (overall) (ha)**	***Eastern German Lignite District* (ha)**
Devastated land	175,677 (100 %)	87,068 (100 %)
Working zone [1]	54,838 (31 %)	31,992 (37 %)
Already reclaimed area	120,838 (69 %)	55,075 (63 %)
... for agriculture	33,999 (19 %)	9,937 (11 %)
... for forestry	53,111 (30 %)	30,620 (35 %)
... water bodies (artificial)	22,139 (13 %)	7,546 (9 %)
... infrastructure [2]	11,690 (7 %)	6,973 (8 %)

[1] inclusive *"reclamation time lag"* and mechanically instable dumps with diverse management restrictions, [2] transport facilities, industrial real estate and housing area

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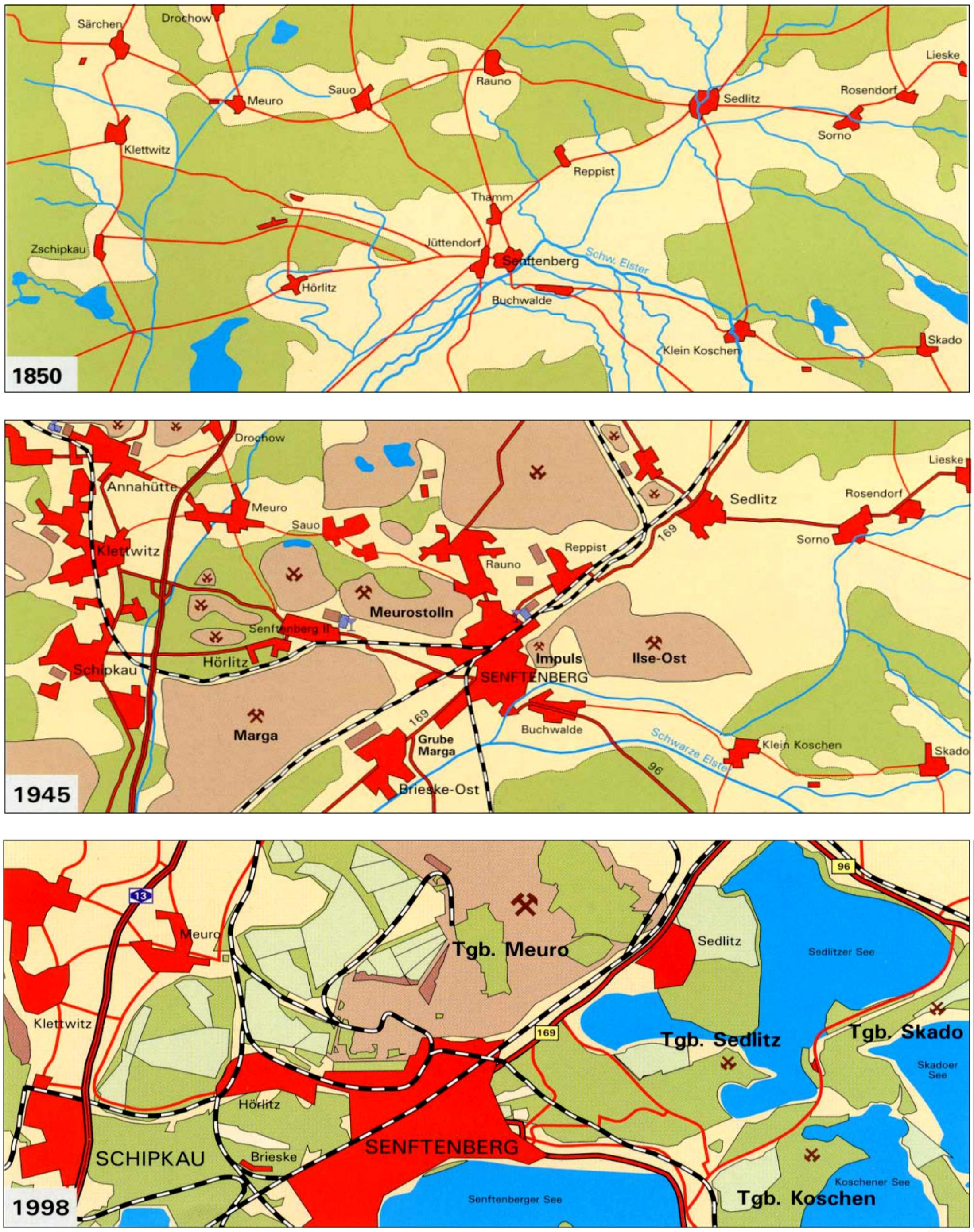

FIGURE 3: LANDSCAPE CHANGE IN THE *EASTERN GERMAN LIGNITE DISTRICT*: 1850 - 1945 - 1998, LOOKING AT THE *"CORE AREA"* AROUND THE CITY OF *SENFTENBERG* (LMBV 1998)

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Rehabilitation of post-mining landscapes

The overall objective of the rehabilitation practice is to establish and promote a designated post-mining land-use concerning site adapted ecosystems, which can be used in different ways but should also fit in the traditional land-use of the region (Schlenstedt et al. 2014). In the case of agroecosystems, mine site reclamation ends, when re-vegetation is achieved as intended and land comes into a regular post-mining after-use. From now on, the management corresponds to *"natural"* (native) agricultural soils (Olschowy 1993, Drebenstedt 1998, 2001). The responsible mining company can sell the reclaimed land to farmers or other private persons.

However, from the ecological point of view restoring fully sustainable, integer and healthy ecosystems is a long-term process taking several decades (Jordan et al. 1987, SER 2004). The *"man-made",* artificial ecosystems develop from an initial, quite simple level of organisation to a complex and functioning biological system over time, which include i.e. the community of soil microbial populations, the accumulation of organic matter and humus layer, and the establishment of nutrient cycle through immobilisation and mineralisation of organic compounds. Because mine soil dynamics are quite high, it turns out rather difficult to predict the long-term ecosystem behaviour on proved cause-effect relationships and thus the biomass potential.

Agricultural reclamation – demands, objectives and procedures

Land devastation by opencast mining results in a considerable loss of fertile farmland (Figure 4 and 5). Thereby, the re-establishment of high-yielding priority areas is of major concern for the agricultural enterprises - all the more as there is rather no chance to expand in the region elsewhere (Gunschera 1998, Haubold-Rosar 2004). Based on ecological principles the most *"valuable"* substrates (i.e. sandy loam, calcareous loam) are subjected to agriculture, while less fertile soils are afforested or reserved for nature preservation (natural succession, *"forest development area"*). Therefore, the core target of overburden2) movement and agricultural restoration is to create soils with a high yield expectation according to the geological presetting (i.e. soil texture and admixtures, soil density, Haubold-Rosar 2001). In that respect, reclamation practice establishes basic soil functions for a manifold, sustainable and site-adapted after-use (food, forage and renewable feedstock).

After levelling and final land preparation (amelioration, loosening, basic fertilisation) the agricultural re-vegetation starts with a special, science-based and under field conditions well-proved *"reclamation crop rotation"* (Haubold-Rosar & Gunschera 2009). In this standard sequence quite unassuming, fast growing and deep rooting annual crops are predominant to promote the soil fertility. The amount of harvest and root residues is high, the biomass removal moderate, thus stimulating the intended humus formation. As Table 3 points out, the atmospheric nitrogen binding lucerne (alfalfa) plays a key role: it covers 40 to 50 % of the cultivated crops. Even more, other legumes and winter cereals take additional 25 to 35 %. In contrast, more humus draining energy crops like winter rape and maize are subordinated (5 to 10 %). With proceeding reclamation, the proportion of cereals can increase to 40 to 45 % at least (Haubold-Rosar 2001, Schlenstedt et al. 2014).

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2) soil material, that lies above the lignite seam (layer)

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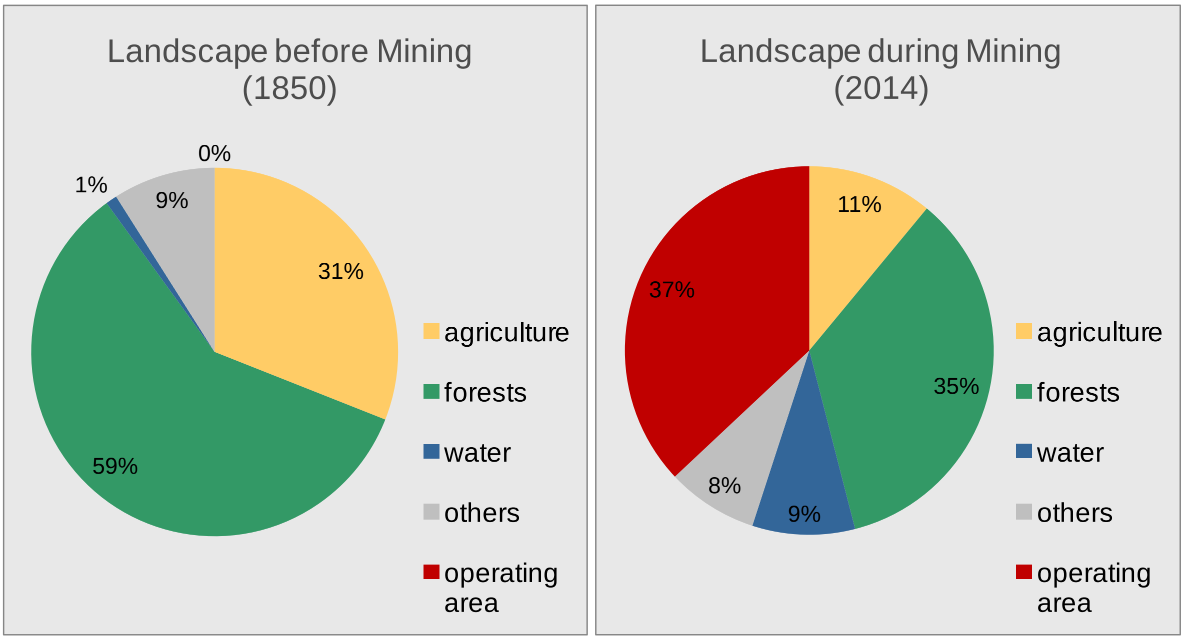

FIGURE 4: RELATIVE SHARE OF LAND USE SYSTEMS BEFORE MINING AND DURING OPERATION (CLAIMED AREA) AND IN THE POST-MINING LANDSCAPE (RECLAIMED AREA)

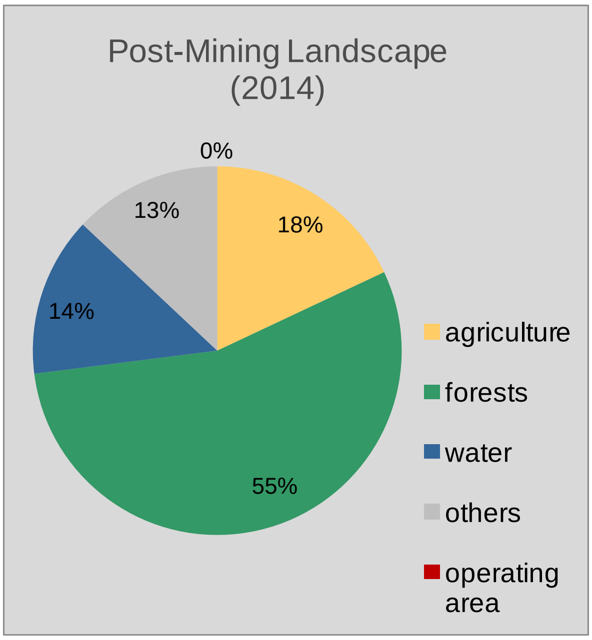

FIGURE 5: RELATIVE SHARE OF LAND USE SYSTEMS IN THE POST-MINING LANDSCAPE (RECLAIMED AREA)

TABLE 3: MANAGEMENT PRACTICE: A SPECIAL CROPPING SYSTEM DESIGNED FOR THE AGRICULTURAL RECLAMATION (GUNSCHERA 1998), THE MAIN FOCUS IS ON THE RESTORATION OF SOIL FERTILITY AS ESSENTIAL CONDITION FOR A SUSTAINABLE AFTER-USE

Year of cultivation	Crop	Comments
Pre-planting		
1	winter rye, broad bean-field pea mixture (e.g. with maize, sunflower), sweet clover, cocksfoot grass	mulching and green manure
First crop rotation period		
2	winter wheat	intermediate crop
3	winter rye	
4 - 7	lucerne-forage grass mixture	plough pan loosening
8	silage maize, winter wheat or winter rye	straw manuring
Second crop rotation period		
9	winter wheat, winter rye or winter rape	organic fertilization with dung
10	forage grass mixture	
11 -12	winter wheat or winter rye	intermediate crop, straw manuring
13 -16	lucerne-forage grass mixture	plough pan loosening

Soil formation ("*from point zero*")

In the *Eastern German Lignite District* approximately 90 % of abandoned mine land are sands and loamy sandy substrates. They have a low plant available water storage capacity in common. But the soil chemical properties are quite variable (Haubold et al. 1998). In fact, there are two basic types of loose rock, according to the stratigraphic sequence (Nowel et al. 1995):

- *Tertiary* (Neogene) sediments - carboniferous and pyrite-containing substrates of the *Miocene* period (2.6 to 23 million years ago); complex of diverse marine and brackish deposits and embedded lignite seams, overlaid by:
- *Quaternary* deposits - non-carboniferous and pyrite-free overburden sediments, predominant from the *Saale* glacial period (130,000 to 300,000 years ago); moraine and glaciofluvial material, dune sands, etc.

Driven by re-vegetation and cropping (biological rehabilitation) mine substrates underlie high soil dynamics over the time (Figure 6, 7 and 8). Initially, dumped substrates are anthropogenic raw soils with a set of growth limiting factors (Schlenstedt et al. 2014). In common, the parent material is free of recent organic matter (humus) and generally lacks plant-available nutrients. At the beginning of the soil development the biochemical activities and nutrient turnover are very slow. Especially nitrogen, phosphorous (<1 mg 100 g^{-1}) and sometimes potassium are plant growth limiting, even for quite unpretentious pioneer and short-rotation tree species (Heinsdorf 1996). Moreover, juvenile soils are mechanically unstable, especially under wet conditions (Haubold-Rosar 2001, Stock et al. 2007).

Accordingly, the soil fertility has to be improved by special measures of reclamation, like amelioration, N, P, K fertilisation and a site-specific crop mixture within the first and second crop rotation period (Haubold et al. 1998). However, it may take several decades to reach stable conditions normally found in natural soils.

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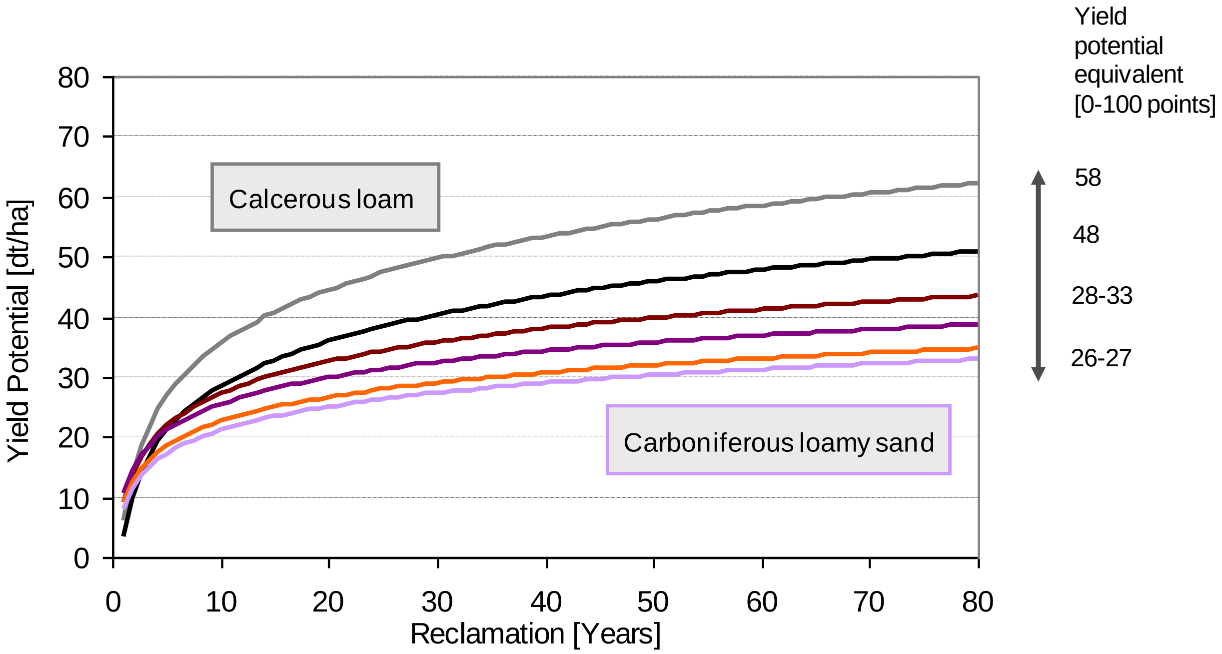

FIGURE 6: DEVELOPMENT OF SOIL FERTILITY AND CORRESPONDING YIELDS ON SOME TYPICAL MINE SOILS ACCORDING TO GUNSCHERA (1998)

"yield potential equivalent": relative scale for soil fertility and yield potential of cereal dominated crop rotations, according to *Soil Quality Rating Index* (SQR), with 100 yielding points as the maximum in *Germany* and <25 points = *"marginal agricultural soil"*

FIGURE 7: AGRICULTURAL RECLAMATION AND SITE WITH GROWING SUNFLOWER FOR BIOFUEL

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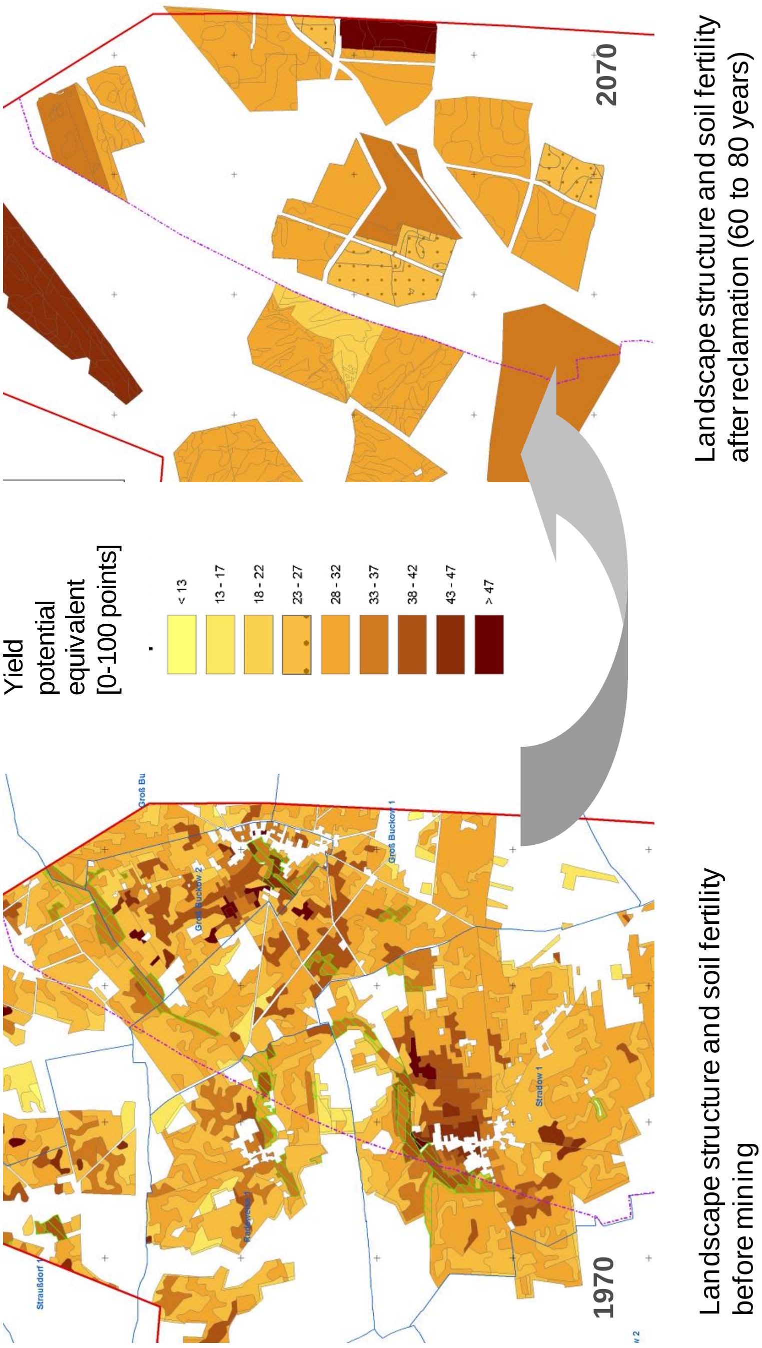

FIGURE 8: LANDSCAPE STRUCTURE AND YIELD POTENTIAL BEFORE AND AFTER MINING; OPENCAST LIGNITE MINE *WELZOW-SÜD*, ACCORDING TO HAUBOLD-ROSAR & KEMPE (2010)

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Tertiary mine soils

The common use of conveyor bridge technology for overburden removal makes a selective dumping of fertile and homogenous soils difficult, especially when the layer thickness of the pre-existing soil material is low or the geological strata are disturbed (Katzur & Böcker 2010). Thereby, unsorted *Tertiary* carboniferous substitutes and mixtures with removed *Quaternary* overburden material are dominating the dumps (about 60 %, Figure 10).

Unfortunately, they show considerable pyrite contents (FeS_2). In the exposed rock ferric sulphide gets rapidly oxidised inducing a strong sulphuric acid formation. Already some months after dumping topsoil pH values drop below 3.0, which leads to strong silicate weathering with phytotoxic aluminium and iron concentrations in the seepage water (Illner & Katzur 1964, Katzur 1998, Katzur & Liebner 1998). Without a long-lasting amelioration (liming, buffering of acids) such anthropogenic soils remain barren of vegetation, sometimes even for decades (*"lunar landscape"*, Knabe 1959, Pietsch 1996).

FIGURE 9: OVERBURDEN CONVEYOR BRIDGE F 60 AT THE OPENCAST MINE JÄNSCHWALDE - THE LARGEST MOVABLE MACHINE IN THE WORD

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Sandy loamy Regosol

of Tertiary bedrock

- finely disturbed lignite, FeS_2-S up to 0.3 mass-%
- pH_{H2O} 5.5 (topsoil) to 3.0 (subsoil)
- intensive mineral weathering and salt dynamics
- initial basic amelioration (0-30 cm)

FIGURE 10: TYPICAL *TERTIARY* MINE SOIL (SANDY TO LOAMY *REGOSOL*) WITH BASIC AMELIORATION OF THE TOPSOIL AND LIGNITE RESIDUES, AFTER 60 YEARS OF UNDISTURBED SOIL FORMATION UNDER A PINE FOREST (*PINUS SYLVESTRIS*)

About 10 to 300 Mg ha^{-1} soil active CaO (!), applied as carbonate ($CaCO_3$) or dolomite ($CaMg(CO_3)_2$), are needed to establish and maintain a *"crop-friendly"* topsoil-pH of 6.0-6.5 against ongoing proton release. Nowadays, limestone gets incorporated with deep rotary tillers (sandy and loamy soils) and fast-running rotary tillers (clay soils) to maximum 100 cm soil depth providing a sufficient rooting zone right from the start (Knoche & Haubold-Rosar 2004). Moreover, the proper basic amelioration ensures a good calcium and magnesium nutrition.

Quaternary mine soils

Because of higher environmental standards since 1990, heaps and dumps are covered with a minimum one-meter layer of fertile *Quaternary* overburden material. In common, such fluvial sediments, glacial sands or boulder clays and till layers, are characterised by growth optimal pH values from 4.5 to 8.0 in the silicate and carbonate buffer range of the soil (Figure 11). Without any acidification potential these raw soils are suitable for cropping. But they need a special basic mineral fertilisation and sometimes small lime applications according to the site quality, type and designated land-use (Haubold-Rosar & Gunschera 2009).

Supplying field crops with nutrients at the right time, quantity and well-balanced is decisive for the success of agricultural reclamation. Thereby, the N, P, K fertiliser requirement of reclaimed sites exceeds the level of arable soils of the surroundings by approximately 1/3. On the other hand, there are usually no deficits in calcium,

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magnesium, sulphur or micronutrients (Haubold-Rosar & Gunschera 2009). Only when the N, P, K nutrition is optimal and the nutrient removal by biomass utilisation is high a fitting supplementary S-fertilisation gets necessary, i.e. for demanding crops, like rapeseed. Actually, neither on *Quaternary* nor *Tertiary* mine soils any micronutrient deficiency occurs. As well there is no evidence for heavy metal toxicity. Even more, the geological background values of pollutants are lower as compared to native soils of the region. But unfortunately, the dominant sandy soils have a quite low water retention and storage capacity for mineral macronutrients.

Sandy Regosol

of Quaternary overburden material

- with clay and loam fragments
- pH$_{H2O}$ 4.5 to 5.5
- „plant-friendly“, no initial lime requirement

FIGURE 11: TYPICAL *QUATERNARY* MINE SOIL (SANDY *REGOSOL*), WITH DIFFERENT SUBSTRATE LAYERS AND THE INITIAL HUMUS FORMATION, AFTER 60 YEARS OF UNDISTURBED SOIL FORMATION UNDER A BIRCH FOREST (*BETULA PENDULA*)

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Cropping potential and development

Moreover, the lack of organic matter, a low nutrient availability and biological activity requires a special site-adapted *"reclamation crop sequence*" in the first decades, analogous to *Tertiary* mine soils. Thus, the major target of *"biological reclamation"* is the establishment of ecological soil functions with an increase of soil fertility, cropping capacity and crop safety by time. Table 4 gives a brief overview about some essential soil chemical and physical target values which should be achieved during the first two crop rotations. These soil quality criteria are binding and reclamation standard.

As Table 5 on page 102 points out, there is a considerable increase of yields with respect to the development of soil functions. In the first crop rotation (1 to 8 years) the cereal equivalents (CE) range between 24 and 32 CE ha^{-1} yr^{-1}. Within 60 to 80 years of management the crop potential amounts 42 to 80 CE ha^{-1} yr^{-1}. For comparison purposes: the average cereal equivalent of native farmland is 46.2 CE ha^{-1} yr^{-1} (*Brandenburg*) and 56.6 CE ha^{-1} yr^{-1} (*Germany*, BMEL 2016). The trend of biomass increase is quite similar. For example: dry matter (DM) yield of lucerne starts with moderate 2.2 Mg ha^{-1} yr^{-1} at the beginning of crop rotation (Table 6) and is 12.5 - 17.1 Mg DM ha^{-1} yr^{-1} after 50 years (Table 7).

However, recent advances in crop breeding indicate much higher yields, even on marginal mine soils. In field-experiments high performance forage *Sorghum* sorts and *Sudan* grass reach 10.7 to 16.0 Mg DM ha^{-1} yr^{-1} in years of above average precipitation in the vegetation period (Table 8).

TABLE 4: *"SOIL TARGET VALUES"* (TOPSOIL) FOR AN AGRICULTURAL LAND-USE, THIS PARAMETERS SHOULD BE ACHIEVED WITHIN 10 TO 16 YEARS OF RECOMMENDED CULTIVATION, HAUBOLD-ROSAR & GUNSCHERA (2009) AND SCHLENSTEDT ET AL. (2014)

Substrate group (mine soils with comparable characteristics and agronomical quality)	**pH_{KCl}**	**C_t 1)**	**BD**	**P**	**K**	**Mg**
		%	**g cm^{-3}**	**mg $100g^{-1}$**		
I Quaternary substrates: carbonate containing loam and slit	6.8-7.2	0.5-1.5	1.65	8	15	9
II Quaternary/Tertiary mixtures: loam and silt	6.5-7.0	1.0-1.5	1.60	7	14	8
III Tertiary substrates: very cohesive, carboniferous, loam, sandy loam and silt	6.0-7.0	1.5-2.0	1.60	7	12	6
IV Quaternary substrates: loamy sand, carbonate containing or carbonate free	6.0-7.0	0.5-0.9	1.60	7	11	6
V Quaternary/Tertiary mixtures: carboniferous, acid-sulphurous loamy sands	6.0-7.0	0.5-0.9	1.60	7	11	6
VI Tertiary substrates: carboniferous loamy sands and sandy loams	6.0-6.5	1.0-1.5	1.50	7	12	6
VII Tertiary or Quaternary substrates and mixtures: poor loamy sands	6.0-6.2	0.5-1.0	1.50	7	9	5

1) soil organic matter (humus), C_t = total carbon, BD = soil bulk density, plant-available P, K and Mg

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TABLE 5: YIELD DEVELOPMENT AND TARGET VALUES IN CEREAL EQUIVALENTS (CE HA^{-1} YR^{-1}) ON AGRICULTURAL USED MINE SOILS IN THE *EASTERN GERMAN LIGNITE DISTRICT* IN ORDER OF DECREASING LAND QUALITY, GUNSCHERA (1998)

Substrate group (mine soils with comparable characteristics and agronomical quality)	Yields in the first decades CE ha^{-1} yr^{-1}			Target value CE ha^{-1} yr^{-1})
	1 to 8 yr	9 to 16 yr	32 to 40 yr	60 to 80 yr
I Quaternary substrates: carbonate containing loam and silt	32	37	58	80
II Quaternary/Tertiary mixtures: loam and silt	32	37	58	80
III Tertiary substrates: very cohesive, carboniferous, loam, sandy loam and silt	30	36	55	67
IV Quaternary substrates: loamy sand, carbonate containing or carbonate free	30	36	54	68
V Quaternary/Tertiary mixtures: carboniferous, acid-sulphurous loamy sands	28	33	42	52
VI Tertiary substrates: carboniferous loamy sands and sandy loams	25	28	40	47
VII Tertiary or Quaternary substrates and mixtures: poor loamy sands	24	26	32	42

CE = *"Cereal equivalent"*: i.e. 0.1 Mg ha^{-1} yr^{-1} corn (87 % dry matter) = 1 CE ha^{-1} yr^{-1};
0.1 Mg ha^{-1} yr^{-1} alfalfa-grass-mixture (21 % dry matter) = 0.13 CE ha^{-1} yr^{-1}

the average CE in *Germany* (2015): 80.9 ha^{-1} yr^{-1} (wheat), 71.7 ha^{-1} yr^{-1} (barley)
the average CE in *Brandenburg* (2015): 70.1 ha^{-1} yr^{-1} (wheat), 64.2 ha^{-1} yr^{-1} (barley)

BMEL (2016)

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TABLE 6: BIOMASS YIELD PROGNOSIS FOR LUCERNE, GRASSLAND AND SILAGE MAIZE ON TYPICAL AGRICULTURAL MINE SOILS (SUBSTRATE GROUP IV AND V) IN THE CASE STUDY REGION AS A FUNCTION OF CULTIVATION AGE (3-31 YEARS), HAUBOLD-ROSAR (2008)

Crop	Harvest year	Reclamation age	Yield	Silage
			Mg DM ha^{-1} yr^{-1}	Mg DM ha^{-1} yr^{-1}
Lucerne	1nd	3	2.2	2.0
	2nd	4	2.5	2.3
	3td	5	2.8	2.6
	1nd	13	4.5	4.1
	2nd	14	4.6	4.3
	3rd	15	4.8	4.4
	1nd	23	5.2	4.7
	2nd	24	5.2	4.8
	3rd	25	5.3	4.9
Grassland farming	1nd	10	3.1	2.9
	2nd	11	3.9	3.6
	1nd	20	3.7	3.4
	2nd	21	4.6	4.2
	1nd	30	4.1	3.8
	2nd	31	5.1	4.7
Silage maize	-	7	6.0	5.5
	-	17	7.1	6.6
	-	27	8.1	7.4

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TABLE 7: BIOMASS YIELDS FOR LUCERNE, SILAGE MAIZE AND FORAGE *SORGHUM* ON TYPICAL AGRICULTURAL MINE SOILS (SUBSTRATE GROUP IV AND V) IN THE *EASTERN GERMAN LIGNITE DISTRICT*, ON-FARM-EXPERIMENTS, WEIß & HAUBOLD-ROSAR (2015)

Crop	Harvest year	Reclamation age	Yield Mg DM ha^{-1} yr^{-1}	Silage Mg DM ha^{-1} yr^{-1}
Hindenberg-Nord				
Lucerne	2nd	+/-50	4.9 - 13.1	4.5 - 12.1
	3rd	+/-50	6.8 - 17.1	6.3 - 15.8
	4th	+/-50	6.3 - 12.5	5.8 - 11.5
Hindenberg-Süd				
Silage maize	-	+/-50	14.0	12.9
Kleinkoschen				
Forage *Sorghum*	-	+/-50	8.9 - 16.9	8.2 - 15.6

TABLE 8: BIOMASS YIELDS OF SOME HIGH PERFORMANCE FORAGE *SORGHUM*, *SUDAN* GRASS AND SILAGE MAIZE ON TYPICAL AGRICULTURAL MINE SOILS (SUBSTRATE GROUP IV AND V) IN THE *EASTERN GERMAN LIGNITE DISTRICT*, MÄRTIN & BARTHELMES (2014)

Crop	Harvest year	Reclamation age	Yield Mg DM ha^{-1} yr^{-1}	Silage Mg DM ha^{-1} yr^{-1}
Forage *Sorghum*	-	10	12.7 - 14.1	11.7 - 13.0
	-	60	14.0 - 16.0	12.9 - 14.7
Sudan grass	-	10	10.7 - 11.7	9.8 - 10.8
	-	60	14.8 - 15.3	13.6 - 14.8
Silage maize	-	10	11.8 - 13.2	10.9 - 12.1
	-	60	15.1 - 15.6	13.9 - 14.4

However, as compared to native agricultural soils in *Germany* mine reclamation soils remain quite unproductive. In many cases even at its best reclaimed fields are

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"marginal land", with less than 30 % of the maximum yields elsewhere. Thus, it is likely that the income for the farmers remains insufficient in the long term (negative contribution margin). Above all, there is a considerable and increasing production risk due to the low water storage capacity, especially in dry years of less than 400 mm rainfall and on insufficiently (shallow, <60 cm) ameliorated acid-sulphurous mine soils. Not surprisingly, this kind of *"underutilised"* and low-yielding land is managed inconsequently.

According to the reclamation objective of stimulating the SOM accumulation, it is clear that the complete, annual removal of crop residues is hardly sustainable in the ecological way and may adversely affect the soil fertility. The establishment of water and nutrient unassuming woody biomass in SRC systems and perennial energy crops may provide an ecological-compatible alternative (Bungart & Hüttl 2001, Quinkenstein et al. 2009). According to Table 9 the aboveground biomass increment of most promising black locust ranges from 2.7 to 10.6 Mg DM ha^{-1} yr^{-1}. These yields correspond already to the biomass level of short-rotation forestry (SRF) on native forest soils in the region. For example, Knoche et al. (2015) report 1.2 to 10.7 Mg DM ha^{-1} yr^{-1} (Ø 4.8 Mg DM ha^{-1} yr^{-1}).

In contrast, more drought-sensitive hybrid poplars and willows show a lower biomass growth in the first rotation period. Under very unfavourable site properties (low water storage capacity, initial soil development) the increment amounts only 0.1 Mg DM ha^{-1} yr^{-1} (Amthauer-Gallardo 2014). Thus the productivity of poplar and willow clones is still under the economic threshold for a commercial successful SRC in *Germany* of about 7 to 8 Mg DM ha^{-1} yr^{-1}, recently calculated by Hartmann et al. (2013) and Kröber et al. (2013).

However, there can be a considerable yield increase expected already from the first to the second rotation period due to the establishment of the root systems and stimulation of sprouting. For example, Horn et al. (2013) point out that biomass growth of some poplar clones (*Max 1*, *2*, *4*, *Androscogin*, *Hybrid* 275) increases by 1.4 to 5.5-times which is +2.1 to +7.9 Mg DM ha^{-1} yr^{-1}. In particular, low-yielding sites show the highest dynamics. In the long run, potential feedstock plantations may improve both the soil fertility and the economic value of reclaimed land (Landgraf & Böcker 2009, Böhm et al. 2011a, b, Knoche et al. 2015).

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TABLE 9: ABOVEGROUND LEAFLESS BIOMASS INCREMENT OF FAST GROWING TREES IN SHORT-ROTATION COPPICES (SRC) ON TYPICAL POST-MINING SITES IN THE *EASTERN GERMAN LIGNITE DISTRICT*

Crop	Rotation cycle	Rotation period / Age	Yield (DM)	Reference
		years	Mg ha^{-1} yr^{-1}	
Black locust	1st	5 - 6	3.0	Böhm et al. (2009)
	2nd to 6th	5 - 6	6.0	Böhm et al. (2009)
	1st	6	1.2 - 7.3	Kanzler et al. (2014)
	1st	3 - 9	3.5 - 8.9	Grünewald et al. (2006)
	1st	1 - 5 1)	2.7 - 10.6	Knoche et al. (2015)
Hybrid poplar	1st	10	2.5 - 3.4	Grünewald et al. (2009)
	1st	3	<0.1 2)	Amthauer-Gallardo (2014)
	1st	3	4.6 3)	Amthauer-Gallardo (2014)
	1st	6	1.6	Kanzler et al. (2014)
	1st	3	0.3 - 0.5	Kanzler et al. (2014)
	1st	14	5.3 - 9.3	Böhm et al. (2011b)
Willow	1st	10	0.7 - 0.9	Grünewald et al. (2009)
	1st	3 - 9	0.5 - 0.8	Grünewald et al. (2006)
	1st	3	0.1 - 0.3	Kanzler et al. (2014)
	1st	3	<0.1 2)	Amthauer-Gallardo (2014)
	1st	3	3.4 - 4.7 3)	Amthauer-Gallardo (2014)

1) Established black locust stands (20 to 43 years) illustrate the growth potential of SRC on developed post-mining sites (without groundwater influence or stagnant moisture). 2) *Quaternary* loamy sand, initial mine soil, 15 years after dumping, 3) carboniferous sandy loam, 60 years of soil development

Commercial energy crops – yield and profit contribution

Forage *Sorghum, Sudan* grass, silage maize

Recent investigations about the cropping potential of energy crops on reclaimed land provide a reliable view of the economic feasibility (Theiß et al. 2014). Looking at the on-farm biogas production chain, the cultivation of forage *Sorghum*, *Sudan* grass and silage maize is a good investment generating a positive income (Table 10). Even young mine reclamation soils can be profitable, not least because of the advances in cropping practice and plant breeding during the last two decades (Fritz et al. 2012, Hartmann & Fritz 2012).

However, the yield expectation on native, well-managed farmland of the region turns out higher and is covering the costs every year. For example, in the high-yielding vegetation period 2011 the profit contribution - revenue minus direct production costs - of *Sorghum* is 256 to 332 € ha^{-1} for mine soils, but 439 to 532 € ha^{-1} on nearby *"unmined"* locations. In general, the yielding potential of forage *Sorghum*, *Sudan* grass and silage maize is quite similar, even when maize in rather rainy summers is superior.

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TABLE 10: YIELD AND PROFIT CONTRIBUTION (PC) OF FORAGE *SORGHUM*, *SUDAN* GRASS AND SILAGE MAIZE DESIGNED FOR BIOGAS PRODUCTION ON MINE SOILS AS COMPARED TO TYPICAL AGRICULTURAL SOILS OF THE REGION, CROPPING PERIOD 2011 TO 2013, FIELD TRIAL AND AVERAGE OF ALL SORTS TESTED, THEIß ET AL. (2014)

Site / Year	Forage *Sorghum*		*Sudan* grass		Silage maize	
	Yield	PC	Yield	PC	Yield	PC
	Mg DM ha^{-1} yr^{-1}	€ ha^{-1}	Mg DM ha^{-1} yr^{-1}	€ ha^{-1}	Mg DM ha^{-1} yr^{-1}	€ ha^{-1}
Welzow **- Mine soil, *Quaternary* pure sand, reclamation age 15 years**						
2011	16.0	256	14.4	177	14.3	273
2012	10.9	-2	8.1	-135	10.7	67
2013	-	-	-	-	-	-
Grünewalde **- Mine soil, *Tertiary* (carboniferous) loamy sand, reclamation age 60 years**						
2011	17.3	332	16.7	277	16.5	457
2012	16.8	240	16.9	334	17.0	479
2013	12.0	0	11.7	-18	12.5	142
Drößig **- Typical agricultural soil of the region, *Quaternary* loamy sand**						
2011	19.1	439	16.5	285	15.0	374
2012	15.0	174	16.2	321	16.4	459
2013	10.2	-63	9.5	-53	12.5	189
Güterfelde **- Typical agricultural soil of the region, *Quaternary* loamy sand**						
2011	20.6	532	16.6	317	20.7	721
2012	19.1	397	14.6	192	20.6	672
2013	15.5	237	13.0	96	18.4	520

Economic assessment of woody biomass

Due to the quite unfavourable growth conditions of poor mine soils farmers are looking for secure and lucrative production alternatives. In order to avoid the set-aside, especially undemanding but fast-growing woody biomass in short rotation coppices (SRC) or alley-cropping systems (ACS) seem promising (Quinkenstein et al. 2009). However, on sandy, groundwater-free mine soils with low water availability poplar hybrids (*Populus* spec.) and willow (*Salix* spec.) cannot meet the economic threshold. In fact, the annual increment of biomass provided for burning overall is far below 5 Mg DM ha^{-1} yr^{-1} (Table 9).

Such the current level for competitive SRC in the region is approximately 6 Mg DM ha^{-1} yr^{-1} (with additional *EU Single Farm Payments*) to 9 – 10 Mg DM ha^{-1} yr^{-1} (without), based on a 20 year investment period with 5 utilisation intervals (Hartmann et al. 2013, Kröber et al. 2013, by discounted cash flow method, Table 10 and 11). However, without EU compensation even the *"regular"* agricultural land use remains in deficit or is generating only low annuities (Hanff & Lau 2016). The critical point of SRC are the establishment costs (tree seedlings and planting). Moreover, a high mortality during the initial phase, especially after dry summers, may turn the whole investment in deficit. Although the economic value of SRC in general increases gradually with each rotation period, finally only groundwater affected priority sites allow a profitable short-rotation cropping (Hartmann et al. 2013).

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TABLE 11: PROFIT CONTRIBUTION (PC) OF SRC DEPENDING ON YIELD AND PRICE FOR WOOD CHIPS, WITHOUT EU SINGLE FARM PAYMENTS (€ HA^{-1}), KRÖBER ET AL. (2013)

Price for wood chips (€ Mg^{-1} DM)	Yield (Mg DM ha^{-1} yr^{-1})			
	8.0	10.0	12.0	14.0
100	-176.0	-53.8	68.4	190.6
110	-103.4	37.0	177.3	317.7
120	-30.8	127.7	286.2	444.7
130	41.8	218.5	395.1	571.8
140	114.4	309.2	504.0	698.8
150	187.0	400.0	612.9	825.9

The actual price for (forest) wood chips 4/2016 in *Germany* (for burning) is 117.7 € Mg^{-1} DM, according to C.A.R.M.E.N (2016). Calculation basis is a water content of 35 mass % at the time of delivery, supply in the range of 20 km, including VAT and flat rates for supply, weighing, etc.

Promising: the multipurpose Black Locust (*Robinia*)

The heat and drought tolerant black locust convinces through its good initial growth under nutrient and water shortage conditions (Peters et al. 2007, Rédei et al. 2011, Figure 12). According to Böhm et al. (2011b) the low-input *Robinia* short-rotation plantations may generate a positive income in the first production period, even on young, low-structured, wind-exposed, nitrogen and phosphorous limited mine soils. With a calculated average biomass increment of 6 Mg DM ha^{-1} yr^{-1} and comparable low planting costs a positive annuity is possible after only 3 to 4 rotation periods, provided that there are no disruptions in the production (Rupprecht 2012).

On the other hand, yields may increase with time due to improved soil quality, stimulated sprouting and increasing stem numbers after the first clear cutting (Knoche & Engel 2012, Knoche et al. 2015). However, considering the advanced material utilisation of black locust in the region 30-year rotation periods are the most lucrative, with net gains up to 6,000 € ha^{-1} at the time of logging (Knoche et al. 2014). This complies with the management practice of the much more important cropping areas in *Southern Europe* (Rédei et al. 2008, 2011, Küchler 2001).

FIGURE 12: BLACK LOCUST FOR SHORT-ROTATION COPPICE (SRC) ON A YOUNG RECLAMATION SITE (10 YEARS AFTER DUMPING), CULTIVATION TEST AND COMPETITIVE VARIETY TRIAL *WELZOW-SÜD*; VEGETATION ASPECT IN THE PLANTING YEAR 2014 AND DURING A FIELD TRIP IN MAY 2016

Conclusions

- At the beginning post-mining farm lands are initial ecosystems on humus poor raw soils with developing soil functions and an instable structure. Not really surprising, the first yields are quite low due to nutrient deficiency and low biological activity. A major concern of the so-called *"biological recultivation"* is to restore the soil fertility gradually by a proper, conserving management. Within the first crop rotation specific topsoil target values must be achieved (cross compliance). Otherwise the land cannot be released from mining supervision and transferred as property. Until then the later owners carry out the initial cultivation by order of the mining company. As a rule, in the *Eastern German Lignite District* the high-yielding, most valuable *Quaternary* overburden substrates, like calcareous loam, sandy loam or loess are reserved for agriculture. Hence, the yield prospects are equal or even higher as compared to the farmland of the surroundings in the long term.

- The typical initial crop rotation on raw soils involves the cultivation of particular stress-tolerant, deep rooting and fast growing perennial plants, with legumes in a key position. Such well-balanced measures have to comply with the legal binding establishment of soil functions at first. However, the public refusal to more biogas plants and the cap of maize input, opens up opportunities to integrate economically attractive *Shorgum* and *Sudan* grass but also other grasses and non-woody energy crops into the farm management. There are relevant cropping and agrotechnical experience and support by various research activities. This also applies to forest-based crops in short-rotation coppices (SRC) and agroforestry systems (AFS). According to on-farm cultivation trials especially the fast-growing, air nitrogen-fixing and stress-tolerant black locust is rather promising with respect to both supporting the ecological situation and the profit contribution on reclaimed land.

- In a practical sense land consolidation refers to homogenous and connected management units, appropriate rectangular field design, sound measures of land improvement (amelioration, deep loosening) and an optimal infrastructure. From this point of view post-mining landscapes offer quite favourable agronomical preconditions for a highly mechanised and profitable production. Moreover, ecological aspects, can be taken into account without reducing the crop potential (integrated land use). The establishment of habitats (hedges, groves) is not only a backdrop and ecological upgrading but also improves the productivity, in particular by microclimatic affects (cross-cutting issue).

- In the case study region Berlin & Brandenburg there is an area potential of about 11,800 ha for the cultivation of energy crops on recultivated lignite mining sites. This area size potential is estimated without the consideration of ecological, economic and political restrictions and barriers. Promising energy crops on recultivation sites are forage *Sorghum*, *Sudan* grass, winter rye and wheat, lucerne, *Miscanthus* and black locust (see Table 12, 13 and 14).

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TABLE 12: SUMMARY OF GROWN AND CULTIVABLE ENERGY CROPS ON LIGNITE RECLAMATION SITES - "*TRAFFIC LIGHT SYSTEM*" IN TERMS OF CULTIVABILITY, PART I (ANNUAL CROPS)

"*Traffic light*"	Plant species / genus	Biomass yield [Mg DM ha-1 yr-1]	Reference	Comments on usage, experience and cultivation
Annual crops				
🟩	Forage *Sorghum* (*Sorghum bicolor)*	3 - 16 (9.5) 9 -17 (13)	M1, R1 GT	profitable cropping alternative to maize, many experiences with cultivation on common agricultural sites in *Berlin & Brandenburg* and on reclamation sites
	Sudan grass (*Sorghum sudanense)*	8 -17 (12.5)	GT	very promising cropping experience on poor reclamation and marginal agricultural soils
	Winter rye (*Secale cereale*)	6 - 8 (7)	R1	important element in the crop rotation, undemanding with a good crop safety, on low-yielding sandy soils superior to wheat
	Winter wheat (*Triticum aestivum*)	7 - 9 (8)	R1	proven in the crop rotation, less demanding with a sufficient crop safety
🟨	Silage maize (*Zea mays*)	13 - 21 (14) 6 - 17 (11.5)	M1 R1	well introduced into agricultural management of reclamation sites, stable yields, but not self-compatible and humus draining

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TABLE 13: SUMMARY OF GROWN AND CULTIVABLE ENERGY CROPS ON LIGNITE RECLAMATION SITES - "*TRAFFIC LIGHT SYSTEM*" IN TERMS OF CULTIVABILITY, PART II (PERENNIAL CROPS)

"*Traffic light*"	**Plant species / genus**	**Biomass yield [Mg DM ha-1 yr-1]**	**Reference**	**Comments on usage, experience and cultivation**
Perennial crops				
🟩	Lucerne (*Medicago sativa*)	2 -17 (9.5)	R1	self-regenerating and with a very important for the re-establishment of soil functions and achieving defined topsoil target values (e.g. humus content, plant available nutrients) on reclamation sites, dominant position in the initial cropping sequence, yields particularly depending on the reclamation age
🟨	*Miscanthus* (*Miscanthus x giganteus)*	(3.1) 4.5 - 25 (31)	M2	not yet grown on reclamation sites, but very promising to be tested due to the good yield expectation on marginal to medium agricultural soils in the region
🟥	Winter rape (*Brassica napus*)	Ø 2.3	R1	only few reliable data, demanding and with a much lower yield potential as on marginal agricultural soils in the region

TABLE 14: SUMMARY OF GROWN AND CULTIVABLE ENERGY CROPS ON LIGNITE RECLAMATION SITES - "*TRAFFIC LIGHT SYSTEM*" IN TERMS OF CULTIVABILITY, PART III (WOODY BIOMASS)

"*Traffic light*"	**Plant species / genus**	**Biomass yield [Mg DM ha-1 yr-1]**	**Reference**	**Comments on usage, experience and cultivation**
Woody biomass				
🟩	Black locust (*Robinia pseudoacacia*)	1 - 11 (6)	R1, GT	overall good experiences with the cultivation on humus poor reclamation sites, most promising multipurpose woody energy crop and pioneer tree species in afforestations, soil improving by assimilation of atmospheric nitrogen (symbiontic *Rhizobia*)
🟨	Poplar hybrides (*Populus x spec*.)	<0.1 - 9 (4.5)	R1, GT	not really convincing because of the high, yield variability even of pre-selected high-yielding and drought tolerant clones, fails on sorption poor sandy raw soils
🟥	Willow hybrides (*Salix x spec.)*	<0.1 - 5 (2.5)	R1, GT	frequent summer drought and the low plant available soil water capacity is growth-limiting, cultivable but with a considerable planting risk

Reference:

M1 = on-farm cultivation on marginal soils in *Berlin & Brandenburg*, Hanff & Lau (2016)

M2 = on-farm cultivation on marginal to medium quality soils in *Berlin & Brandenburg* - investigations in two stands in South *Brandenburg* (*Lusatia*), FORBIO (2016)

R1 = on-farm cultivation on reclamation sites, Haubold-Rosar (2008), Weiß & Haubold-Rosar (2014, 2015), Haubold-Rosar et al. (2015, 2016), diverse authors regarding woody biomass

GT = growing trials on reclamation sites, Märtin & Barthelmes (2014), diverse authors regarding woody biomass

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FOSTERING SUSTAINABLE FEEDSTOCK PRODUCTION FOR ADVANCED BIOFUELS ON UNDERUTILISED LAND IN EUROPE

AGRONOMIC FEASIBILITY

ANNEXES

This project has received funding from the European Union's Horizon 2020
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ANNEX 1

"Cropping App"

Agronomic profiles of cultivable crops for disused sewage irrigation fields and lignite reclamation sites in *Berlin & Brandenburg*

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691846.

(1) *Zea mais* L.

Common name	maize, forage maize, silage maize, corn, sweet, mielie
Class / type	C4 plant, tall summer annual grass (*Poaceae*)
Typology	thermophilic forage crop (silage), worldwide most important energy crop (fermentation, coferment with the highest energy yield) and lignocellulosic crop (ethanol, raw material for bioplastics)
Native	*Mexico*, widely cultivated from the tropical to temperate climate zone
Yield expectation / biomass production at sewage farms	not yet cultivated on disused irrigation fields, on marginal agricultural land in *Berlin & Brandenburg*: 13 - 21 Mg DM ha^{-1} yr^{-1} (biomass) and 5 - 6 Mg DM ha^{-1} yr^{-1} (corn)
Yield expectation / biomass production at reclamation sites	in cultivation trials and on-farm: (6) 11 - 17 Mg DM ha^{-1} yr^{-1} (biomass), depending on the reclamation age, soil quality, annual weather conditions and choice of variety
Growing season	April / early May to September / October
Soil requirements	prefers well drained, nutrient rich loamy, quite fertile soils with a crumbly-dry soil tilth, optimal pH between 6.5 and 7.5, tolerates salinity (4 - 10 dS m^{-1})
Phytoremediation & soil improvement	promising for phytoremediation (phytostabilisation, phytostimulation, phytovolatilization and rhizodegradation) because of the high aboveground biomass formation
Growth limiting factors / cultivation risks	summer drought, low cold tolerance - late frosts <-3/4 °C are leading to the die back of leaves, even light early frosts (-1 °C) can kill the whole plant, acidification and lack of plant-available macronutrients (NPK), waterlogging and swamp soils, pests and various adapted weeds are calling for an intensive crop protection
Agronomic features	not self-compatible main fruit with a very high energy and fertilizer (NP) demand, although a C4 plant quite water consuming due to the high biomass yield, humus draining crop, continuous cultivation over several years results in "soil tiredness" and high nitrate leaching, but good integrable in the cereal crop rotation (at most 20 %)
Irrigation	mostly non-irrigated, but in summer dry years worthy for irrigation both as food and energy crop
Harvest	fully mechanised by maize choppers, dry matter content 28 – 35 %

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(2) *Sorghum bicolor* L. (Moench) and hybrids

Common name	*Sorghum*, black amber, chicken corn
Class / type	C4 plant / summer annual grass (*Poaceae*)
Typology	sugar, energy (fermentation, coferment), forage (silage) and lignocellulosic crop (biofuel, bioplastics)
Native	tropical and subtropical North and East *Africa*, widely cultivated from the tropical to the temperate climate zone
Yield expectation / biomass production at sewage farms	yield potential uncertain, a first cropping experiment on the disused irrigation field *Cottbus-Saspow* (FORBIO 2016): 5 - 8 Mg DM ha^{-1} yr^{-1} - only seedbed preparation without any fertilization and plant protection (!)
Yield expectation / biomass production at reclamation sites	in several cultivation tests: 9 - 17 Mg DM ha^{-1} yr^{-1} depending on substrate type, reclamation age, soil fertility, grown variety and annual weather conditions, in accordance with the recommended cropping practice
Growing season	mid-May to September / October
Soil requirements	rather low soil requirements, but highest yields on well drained loamy soils with an optimum pH range between 6.5 and 7.5, good nutrient efficiency and drought tolerance
Phytoremediation & soil improvement	soil preserving and improving cropping alternative to silage maize, very deep rooting
Growth limiting factors / cultivation risks	water availability, early summer drought during emergence of the seed, quite sensitive to cold, especially late frosts
Agronomic features	seed-propagated annual main fruit and catch crop (e.g. with winter wheat, winter rye), in contrast to maize no important harmful organisms and pests, self-compatible
Irrigation	so far non-irrigated, but irrigation is worth considering
Harvest	fully mechanised by maize choppers, dry matter content 28 – 35 %

(3) *Sorghum sudanense* Stapf, hybrid *S. bicolor* and *S. virgatum*

Common name	*Sudan* grass, Garawi
Class / type	C4 plant, summer annual grass (*Poaceae*)
Typology	energy (fermentation, coferment), forage crop (silage) and promising lignocellulosic crop
Native	tropical and subtropical North and East *Africa*, most valuable forage crop in the *USA*
Yield expectation / biomass production at sewage farms	no reliable data, not yet established as energy crop
Yield expectation / biomass production at reclamation sites	according to running cultivation tests and competitive variety trials on different mine soils: 8 - 17 Mg DM ha^{-1} yr^{-1} depending on substrate type, reclamation age, soil fertility, grown variety and annual weather conditions
Growing season	mid-May to September / October
Soil requirements	wide variety of soils, good drought tolerance (much better than maize), undemanding with a high nutrient and water use efficiency, but prefers moderate moisture soils
Phytoremediation & soil improvement	soil improving by intensive rooting and heavy metal accumulation in the aboveground biomass (phytoextraction), easily biodegradable root residues, good root penetration (subsoil loosener)
Growth limiting factors / cultivation risks	likes warmth (summer temperatures >25 °C are growth promoting) and is quite sensitive to late frosts and soil compaction, during emergence very sensitive to weeding
Agronomic features	self-compatible cropping alternative to forage maize, as main fruit and catch crop, but also suitable for green manure, less yield effecting harmful organisms, pests unknown but suppresses some nematode species and weed
Irrigation	so far non-irrigated, but irrigation is worth considering
Harvest	fully mechanised by maize choppers, dry matter content 28 – 35 %

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(4) *Triticum aestivum* L.

Common name	winter (summer) wheat
Class / type	C 3 plant, annual grass (*Poaceae*)
Typology	one of the most important food, forage, energy (burning of straw) and lignocellulosic crops - whole plant to biofuel and raw material for the chemical industry
Native	*Mediterranean* region, *Near East* as the "cradle of arable farming"
Yield expectation / biomass production at sewage farms	no cropping experiments on disused irrigation fields
Yield expectation / biomass production at reclamation sites	integral element of the first and second crop rotation: 8 - 9 Mg DM ha^{-1} yr^{-1} (biomass: corn and straw) and 2 - 5 Mg DM ha^{-1} yr^{-1} (corn), in particular depending on soil quality, reclamation age, annual weather conditions and harvest date
Growing season	September - December (sowing even in December possible), April to August in the following year
Soil requirements	comparatively demanding cereal, needs a well-balanced water supply and fertilisation (NPK, Ca, Mg, S)
Phytoremediation & soil improvement	erosion control, as organic matter source soil building
Growth limiting factors / cultivation risks	winter frost resistant (-20 °C), middle drought tolerance, but early summer drought causes up to 30 % yield depressions, needs a consequent plant protection
Agronomic features	main, catch and cover crop in the cereal crop rotation, good weed suppressor
Irrigation	rainfed, but profitable for irrigation
Harvest	fully mechanised by combined harvesters, the straw remains on the field and serves for humus reproduction, furthermore, the straw is baled for bedding or energy purposes, dry matter content (corn) 85 %

(5) *Secale cereale* L. (hybrides, population sorts)

Common name	winter (summer) rye
Class / type	C3 plant, annual grass (*Poaceae*)
Typology	important food, forage and energy (burning of straw) crop, lignocellulosic crop - whole plant to biofuel and raw material for the chemical industry
Native	*Mediterranean* region, North *Syria*
Yield expectation / biomass production at sewage farms	no cropping experiments on disused irrigation fields, on regular managed irrigation fields: 5 - 7 Mg DM ha^{-1} yr^{-1} (biomass: corn and straw)
Yield expectation / biomass production at reclamation sites	fixed component of the first and second crop rotation: 6 - 8 Mg DM ha^{-1} yr^{-1} (biomass: corn and straw), 2 - 6 Mg DM ha^{-1} yr^{-1} (corn) depending on soil quality, reclamation age, annual weather conditions and harvest date
Growing season	September - December, March / April to August
Soil requirements	less demanding, even on sandy soils worth cultivating, but for high yields a balanced water supply and high fertilizer input are necessary
Phytoremediation & soil improvement	soil improvement by intensive deep rooting, erosion control
Growth limiting factors / cultivation risks	very winter frost resistant (-25 °C), middle drought tolerance, but early summer drought causes up to 30 - 40 % yield depressions, needs a consequent plant protection
Agronomic features	main plant in the cereal crop rotation with a good yield stability, cover crop
Irrigation	mostly non-irrigated, but profitable for irrigation
Harvest	fully mechanised by combined harvesters, the straw remains on the field (humus reproduction), is baled for bedding or energy purposes, sometimes as green manure, dry matter content (corn) 85 %

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(6) *x Triticale* (Tscherm.-Seys. ex Müntzing)

Common name	winter (summer) triticale
Class / type	C 3 plant, annual grass (*Poaceae*)
Typology	important food, forage, energy (burning of straw) and lignocellulosic crop - whole plant to biofuel and raw material for the chemical industry
Native	new breeding in *Europe* (late 19th century, 1930s), crossing between wheat and rye cultivars, a further breeding progress is likely
Yield expectation / biomass production at sewage farms	no cropping experiments on disused irrigation fields
Yield expectation / biomass production at reclamation sites	can be integrated in the first and second crop rotation instead of wheat or rye, on marginal sites in *Berlin & Brandenburg*: 4 - 6 Mg DM ha^{-1} yr^{-1} (biomass: corn + straw), 2 - 4 Mg DM ha^{-1} yr^{-1} (corn)
Growing season	September / October - December, April to August
Soil requirements	less demanding than wheat, but needs a well-balanced water supply and fertilisation (N, P, K, Ca, Mg, S)
Phytoremediation & improvement	no reliable information
Growth limiting factors / cultivation risks	good winter hardiness (-20 °C), but early summer drought can cause up to 30 - 40 % yield depressions
Agronomic features	main crop in the cereal crop rotation, good resistance against pathogenic fungi
Irrigation	mostly non-irrigated, but seems to be lucrative for irrigation
Harvest	fully mechanised by combined harvesters, thereby the straw remains on the field for humus reproduction or is baled for bedding and energy purposes

(7) *Helianthus annuus* L.

Common name	sunflower
Class / type	summer annual herbaceous C3 plant
Typology	thermophilic food (edible oil) and energy crop (biofuel, special oil, staw residuals for burning), lignocellulosic crop with triglycerides for the chemical-technical industry (e.g. pharmaceuticals)
Native	*North* and *Central America*
Yield expectation / biomass production at sewage farms	in the region cultivated on a significant scale since the early 1990s, but no cropping experience on disused irrigation fields, on marginal soils in *Berlin & Brandenburg*: 8 - 9 Mg DM ha^{-1} yr^{-1} (biomass), 1.5 - 1.7 Mg DM ha^{-1} yr^{-1} (corn)
Yield expectation / biomass production at reclamation sites	no reliable data, yields probably strongly depend on the reclamation age and soil quality
Growing season	April / May to September / October
Soil requirements	prefers deep and well drained, nutrient and humus rich loamy soils with a high plant available water storage, optimal pH between 6.0 and 7.0, prospers in the dry and warm continental minted climate
Phytoremediation & soil improvement	suitable for heavy metal phytoextraction because of its high aboveground biomass, improves the soil tilth as forecrop of winter wheat and maize
Growth limiting factors/ cultivation risks	although thermophilic sensitive to summer drought, advantageous are dry maturity and harvest periods, sensitive with regard to waterlogging and silting of the surface, some chewing aphids, sensitive to weeds and fungi (white mold, *Sclerotinia*)
Agronomic features	main fruit and catch crop with a very high energy input, not self-compatible, cropping-free period 4 to 5 years, further diversification of the cereal rotation, because of the inflorescences high ecological value
Irrigation	not worthy for irrigation, sprinkling promotes fungal attack (*Sclerotinia*)
Harvest	fully mechanised by forage harvesters or field choppers, dry matter content (corn) 82 - 88 %

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(8) *Panicum virgatum* L.

Common name	switchgrass, tall prairie grass, panic raide, blackbent, wild redtop, *Virginia* grass, thatchgrass, *Wobsqua* grass
Class / type	C4 plant, tall perennial grass (*Poaceae*)
Typology	energy (fermentation, coferment, burning, pyroloysis), fiber and lignocellulosic crop, forage crop, diverse material utilisation
Native	*North American* prairies (*Great Plaines*), *USA* to *Mexico*
Yield expectation / biomass production at sewage farms	no reliable data, not yet established as energy crop, under optimal growth conditions in *Western Germany*: 25 Mg DM ha^{-1} yr^{-1}, first cultivation trial established by FORBIO (2016)
Yield expectation / biomass production at reclamation sites	no reliable data, not yet established as energy crop, but worth considering
Growing season	mid-May / June to October (February / March)
Soil requirements	tolerates a wide range of edaphic conditions, but prefers sandy-loamy soils, low water and nutrient requirements (good efficiency), needs a soil pH >5.0, tolerates a moderate salinity up to 4 dS m^{-1}
Phytoremediation & soil improvement	soil-conserving and even soil-building benefits by intensive rooting, suitable for phytoextraction of heavy metals, easily biodegradable root residues, the species allows a minimum- or no-till technology
Growth limiting factors / cultivation risks	likes warm summer temperatures, 17 to 32 °C are growth optimum, but very sensitive to late frost (-10 °C) and competing weeds, especially in the regrowth period
Agronomic features	low-input multipurpose main and catch crop, managed with 1 to 2 cuttings per year
Irrigation	in general non-irrigated, needs an annual rainfall >450 mm
Harvest	fully mechanised by field choppers, combined mowers and balers, dry matter content >85 %

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(9) *Miscanthus x giganteus* J.M. Greef & Deuter, (*Miscanthus sinensis* Andersson)

Common name	*Miscanthus*, elephant grass, *Chinese* silver grass, miscantho
Class / type	C4 plant, perennial tall grass (*Poaceae*)
Typology	permanent energy (fermentation, coferment, burning, pelletisation, briquetting, pyroloysis), fiber and lignocellulosic crop, diverse material utilisation
Native	East *Asia* (Central *Japan*, *Korea*, *China*), subtropical to tropical zone, commonly on ruderal and abandoned sites of the maize cropping area
Yield expectation / biomass production at sewage farms	not yet established as energy crop on disused irrigation fields, first reliable on-farm data for typical agricultural soils of the region: 5 - 20 (31) Mg DM ha^{-1} yr^{-1} (FORBIO 2016), depending on plant available water, species, genotype and stand age
Yield expectation / biomass production at reclamation sites	no reliable data, not yet established as energy crop, under favourable growth conditions in *Western Germany*: up to 25 Mg DM ha^{-1} yr^{-1}, ranks among the most high-yielding energy crops
Growing season	mid-April / June to September / October
Soil requirements	tolerates a wide range of edaphic factors, prefers loamy and clay soils, but has a high water and nutrient efficiency, avoids waterlogging and soil compaction
Phytoremediation & soil improvement	suitable for phytoremediation due to intensive rooting and high aboveground biomass
Growth limiting factors / cultivation risks	likes a moderate precipitation with 500 to 600 m yr^{-1}, mean annual temperature >8 °C and warm summers, but strong summer drought is growth limiting, rather poor soil frost tolerance, very sensitive to weed in the first year, pests and diseases irrelevant
Agronomic features	low-input multipurpose main fruit with a cropping period over 20 years, optimal harvest after 4 to 5 years, nowadays several high-yielding and overwintering genotypes on the market, fully mechanised planting of rhizome
Irrigation	in general non-irrigated, irrigation is worth considering
Harvest	fully mechanised by maize choppers, silage harvesters or baling presses, dry matter content 15 - 45 %

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(10) *Dactylis glomerata* L.

Common name	cocksfoot, cocksfoot grass, orchard grass, erba mazzolina
Class / type	C3 plant, perennial grass (*Poaceae*)
Typology	pasture for cattle (grazing, green fodder, hay), sugar and energy crop (fermentation, coferment)
Native	*Eurasia* and North *Africa*
Yield expectation / biomass production at sewage farms	actually not cultivated, but part of the seminatural grass vegetation, on marginal sites in *Berlin & Brandenburg*: 2 - 4 Mg DM ha^{-1} yr^{-1}
Yield expectation / biomass production at reclamation sites	important mixing part of lucerne (lucerne-grass mixtures), thereby in total: 2 - 17 Mg DM ha^{-1} yr^{-1}, yield strongly depending on the reclamation age and soil quality
Growing season	May to September / October (mowing in June to August)
Soil requirements	tolerates a wide range of edaphic conditions, even moderate fertile soils, but prefers well drained, nutrient rich loamy soils with a pH 5.8 to 7.0, undemanding with respect to nutrient supply, considerable Al and acid tolerance
Phytoremediation & soil improvement	suitable for phytostabilisation, phytostimulation, phytovolatilization and rhizodegradation of organic pollutants, hydraulic and erosion control by year-round ground cover
Growth limiting factors / cultivation risks	strong summer drought, lack of plant-available macronutrients (NPK), waterlogging, moderate frost tolerance (-12 °C)
Agronomic features	self-regenerating, important as mixing partner for lucerne in the initial crop rotation on reclamation sites, like lucerne up to 3 - 4 cuttings per year, main fruit and catch crop
Irrigation	non-irrigated, not worthy for irrigation
Harvest	fully mechanised by rotary mowers with loader, and combined harvesters, dry matter content 15 - 54 % depending on the harvest date and precipitation

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(11) *Arundo donax* L.

Common name	giant reed, common reed, giant cane, wild cane, *Spanish* cane
Class / type	C3 plant, perennial grass (*Poaceae*)
Typology	important energy (fermentation, coferment, burning, pyroloysis) and lignocellulosic crop, medical plant, diverse material utilisation (ornamentals), fibre plant
Native	East and South *Asia* (*Iran*, *Iraq*, *India*, *Bangladesh*, *Korea*, *Gulf States*), common in the subtropical zone, introduced into the *Mediterranean* region in ancient times
Yield expectation / biomass production at sewage farms	no reliable yield data, negligible cropping experience, not introduced to agricultural practice in *Germany*
Yield expectation / biomass production at reclamation sites	not yet cultivated, no reliable data
Growing season	mid-May / June to September / October to March
Soil requirements	tolerates a wide range of ecological conditions and soils (light sandy to heavy clay), but a high biomass is associated with wetlands and riparian habitats, prefers well-drained soils with a year-round even water supply, high water and nutrient efficiency, good acid, salt and heavy metal tolerance
Phytoremediation & soil improvement	despite the high biomass production relatively low translocation of heavy metals in the aboveground biomass
Growth limiting factors / cultivation risks	likes warmth and moist, optimum average temperature in the growing season approx. 19 °C, even though it tolerates moderate and singular frost the poor freeze resistance of the rhizomes inhibits cultivation in the case study region, sensitive to high soil compaction and water shortage
Agronomic features	low-input multipurpose crop, because of the insufficient rhizome winter hardiness in East *Germany* no permanent crop, no known ongoing threats to this species
Irrigation	in general non-irrigated, rainfed at >450 mm yr^{-1}
Harvest	fully mechanised by modified maize choppers or baling presses, dry matter content 50 - 65 %

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(12) Permanent or temporary grassland, grass mixtures

Common name	pasture, meadow, grassland, field, grazing land
Class / type	several annual / perennial grasses (*Poaceae*) and diverse herbs, in general C3 plants
Typology	forage crops, lignocellulosic crops
Native	semi-natural vegetation, grass fallow and grass seeding
Yield expectation / biomass production at sewage farms	first yield data on disused irrigation fields (FORBIO 2016): 2 - 4 Mg DM ha^{-1} yr^{-1}, as landscape maintenance with one cutting just before ripening of the dominating grasses, in addition, special herb mixtures for landscape maintenance: about 3 Mg DM ha^{-1} yr^{-1}
Yield expectation / biomass production at reclamation sites	as regular meadow management on marginal grassland in the case study region *Berlin & Brandenburg*: 2 - 3 Mg DM ha^{-1} yr^{-1}
Growing season	March / April to November
Soil requirements	undemanding, species combination is adapted to the site conditions, in particular the water regime is biomass limiting, to a lesser extent the nutrient availability, growth optimal pH range 6.5 to 7.5
Phytoremediation & soil improvement	phytodegradation of organic pollutants and phytoextraction of heavy metals, soil conserving and safeguarding at hazardous areas
Growth limiting factors / cultivation risks	summer drought causes early ripening
Agronomic features	landscape maintenance (nature protection, conservation of a biodiverse open grassland), permanent grassland without earning targets needs no special management, establishment of permanent vegetative cover systems for contaminated soils and abandoned sites advisable
Irrigation	non-irrigated, not worthy for irrigation (no added value)
Harvest	fully mechanised by cutter-loaders and cutter-loaders, dry matter content 28 - 65 %, depending on the harvest date and precipitation

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(13) *Brassica napus* L. and hybrids

Common name	winter (summer) rape, rapeseed, oilseed rape
Class / type	C3 plant annual flowering herb
Typology	most important food (rapeseed oil) and forage crop (silage), energy crop (fermentation, coferment, biodiesel, platforms for the chemical industry and pharmacy), utilisation of rape straw
Native	East *Mediterranean* region, cosmopolitan
Yield expectation / biomass production at sewage farms	no cropping experience on disused irrigation fields, on marginal soils in *Berlin & Brandenburg*: 2 - 3 Mg DM ha^{-1} yr^{-1} (rapeseed)
Yield expectation / biomass production at reclamation sites	limited reliable data available, in the initial crop rotation on a young *Quaternary* mine soil: 0.3 - 1.5 Mg DM ha^{-1} yr^{-1} (rapeseed) and in average 2.3 Mg DM ha^{-1} yr^{-1} (corn and straw)
Growing season	August-November to July / August (hibernation)
Soil requirements	prefers deep loamy soils with a good water supply and a growth optimal pH between 6.5 and 7.5
Phytoremediation & soil improvement	promising for phytoextraction of heavy metals, ploughless cultivation possible, improves the soil tilth as intensively rooting forecrop
Growth limiting factors / cultivation risks	summer drought leads to uneconomic yields, but also sensitive to waterlogging and plough pan, winterkilling in case of an insufficient snow cover, needs intensive NPK and S fertilisation, sensitive to stalk decay (*Phoma*, *Sclerotinia*), club-root (*Plasmodiophora brassicae*), diverse insect pests (cabbage stem flea beetle, *Meligethes*)
Agronomic features	not self-compatible main fruit, also catch and forecrop, important supplement of the cereal crop rotation and suitable for green manure - the straw remains on the field, but as for all cabbage crops a very demanding cultivation
Irrigation	in general non-irrigated, but worthy for irrigation
Harvest	fully mechanised by combined harvesters (threshing of stalks)

(14) *Medicago sativa* L.

Common name	lucerne, alfalfa, common purple lucerne, purple medick, *Spanish* trefoil
Class / type	C3 plant, perennial forage legume (*Fabaceae*)
Typology	worldwide most cultivated forage crop for cattle (grazing, hay, silage), sugar and energy crop (fermentation, coferment)
Native	south-central *Asia* temperate zone, first cultivation in ancient *Iran*
Yield expectation / biomass production at sewage farms	no reliable data, actually not cultivated on disused irrigation fields, on marginal sites in *Berlin & Brandenburg* with an average growth of 7 Mg DM ha^{-1} yr^{-1}
Yield expectation / biomass production at reclamation sites	2 - 17 Mg DM ha^{-1} yr^{-1} strongly depending on the reclamation age substrate quality, soil fertility, rooting layer, cutting frequency (3 to 4 cuttings per year) and harvest date
Growing season	April to September / October (mowing June to September)
Soil requirements	tolerates a wide range of edaphic conditions, but prefers well drained, deep loamy soils with a growth-optimum pH between 5.8 and 7.2, quite undemanding and good drought tolerant due to the deep rooting, symbiontic nitrogen-collecting plant, moderate salinity tolerance (4 - 10 dS m^{-1})
Phytoremediation & soil improvement	atmospheric nitrogen binding and high root biomass formation, pre-adapted to higher uptake rates of toxic hydrocarbons and heavy metals, very important for humus accumulation, soil life and the establishment of nutrient cycling (nitrogen, phosphorous)
Growth limiting factors / cultivation risks	attacked by various pests and pathogens, permanent waterlogging causes growth retardation, sometimes boron, copper and molybdenum deficiency, good frost tolerance (killing temperature -25 °C)
Agronomic features	forage crop with the highest feeding value, self-regenerating, very important function for the re-establishment of soil functions, dominating position in the initial crop rotation, good forecrop (after 3 years) for cereals, potatoes and maize
Irrigation	in general non-irrigated, but irrigation is promising
Harvest	fully mechanised by cutters and cutter-loaders, usually baled, dry matter content 18 - 35%

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(15) *Silphium perfoliatum* L.

Common name	mixed *Silphie,* cup plant
Class / type	C3 plant, perennial shrub
Typology	permanent energy (fermentation, coferment), forage (silage) and lignocellulosic crop
Native	North *America*, widely cultivated from the tropical to the temperate climate zone
Yield expectation / biomass production at sewage farms	no reliable data, not yet established as energy crop in *Berlin & Brandenburg*, yield potential uncertain, up to now cultivation for scientific purposes, under optimal growth conditions in *Eastern Germany*: 13 - 18 Mg DM ha^{-1} yr^{-1}, first cultivation trial by FORBIO (2016)
Yield expectation / biomass production at reclamation sites	no reliable data, not yet established as energy crop, suitability for cropping needs to be proved
Growing season	May / June to August / September
Soil requirements	undemanding, comparatively good drought tolerance, cropping alternative to forage maize, best growth on soils rich in humus with a good water supply, growth optimal pH range 6.6 to 7.8
Phytoremediation & soil improvement	soil improving by intensive rooting and easily biodegradable root residues, soil humus accumulating, erosion protection
Growth limiting factors / cultivation risks	frosts events and strong summer drought lead to growth retardation, especially young plants are highly endangered by weeds and fungi (white mold, *Sclerotinia*), sensitive to waterlogging, animal pests are not yield relevant
Agronomic features	main and catch crop, mixed seed with maize, propagation by seedlings rather demanding and costly, on the other hand seeding is quite risky, as permanent crop with ecological benefits due to the long flowering period and high production of nectar in late summer
Irrigation	permanent rainfed, but irrigation is worth considering
Harvest	fully mechanised by forage harvesters or field choppers, dry matter content 25 - 30 %

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(16) *Reynoutria sachalinensis* (F. Schmidt)

Common name	*Sachalin* knotweed, *Japanese* knotweed, giant knotweed
Class / type	perennial C3 plant (weed), hibernation by self-regenerating rhizomes
Typology	food, energy (fermentation, coferment, burning, pyrolysis) and lignocellulosic crop, promising medicinal plant
Native	North East *Asia*, Northern *Africa*, neophyte, invading weed starting from ruderal and abandoned sites
Yield expectation / biomass production at sewage farms	no reliable yield data, growth and cultivation potential uncertain, in first pot experiments: 5 - 15 Mg DM ha^{-1} yr^{-1}
Yield expectation / biomass production at reclamation sites	not yet tested, but overall quite vital and competitive, since a spreading neophyte no cropping recommendation so far
Growing season	April to October
Soil requirements	undemanding, tolerates a wide variety of soils, distribution especially on ruderal and poor soils, but highest yields on wet, loosely bedded and good aerated substrates with a growth optimal pH between 6.5 and 7.5, obviously very heavy metal tolerant
Phytoremediation & soil improvement	suitable for the phytoextraction of several heavy metals, combines a high biomass increment and pollutant uptake with a considerable translocation rate into the shoot
Growth limiting factors / cultivation risks	young plants are sensitive to early / late frost and severe early summer drought
Agronomic features	conceivable as self-compatible and re-germinating main crop, propagation by seedlings and root-sprouts possible, yield relevant pathogens and animal pests are unknown, unfortunately no tested or registered sorts for energy cropping available on the market, as invasive species discussed controversially
Irrigation	non-irrigated, needs-based watering not yet investigated
Harvest	fully mechanised by forage harvesters and field choppers possible, dry matter content 35 %

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(17) *Amaranthus* L. ssp. (genus)

Common name	amaranth, edible amaranth, *Chinese* spinach
Class / type	C4 plant, genus of summer annual and short-lived perennial shrubs, so-called pseudocereals
Typology	thermophilic food, forage, energy (fermentation, coferment) and lignocellulosic crop
Native	approx. 70 cosmopolitan species, first cultivated in ancient Middle and South *America ("holy plant of the Mayas & Aztecs"),* one of the oldest crop plants
Yield expectation / biomass production at sewage farms	in principle cultivable, but not yet established in *Berlin & Brandenburg*, first encouraging cultivation experiments in South and *Western Germany*: as a catch crop with approx. 8 Mg DM ha^{-1} yr^{-1} (biomass) and 2 - 3 Mg DM ha^{-1} yr^{-1} (corn)
Yield expectation / biomass production at reclamation sites	no reliable data, not yet tested as energy crop on reclamation and abandoned sites, for this basic cropping properties must be examined
Growing season	April / May to August / October
Soil requirements	undemanding, well adapted to dry and nutrient poor soils, but high yields on humic loamy soils, sensitive to nitrogen oversupply
Phytoremediation & soil improvement	phytoextraction of diverse heavy metals already proven
Growth limiting factors / cultivation risks	early and late frost, strong summer drought, sensitive to weed competition in the early sprouting period, but no yield relevant pests
Agronomic features	catch crop and permanent culture, self-compatible, among them some invasive species
Irrigation	in general non-irrigated, but irrigation is worth considering
Harvest	fully mechanised by forage harvesters or field choppers

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(18) *Salix x spec.* (pure species and hybrids, high-yielding clones)

Common name	willow, sallow
Class / type	fast-growing medium-sized pioneer tree species
Typology	energy (burning, pyrolysis) and lignocellulosic crop in short-rotation coppices (SRC), plantations and forests, medical plant
Native	cold and temperate regions of the northern hemisphere
Yield expectation / biomass production at sewage farms	first cropping experiments on disused irrigation fields with mixed results: <0.1 - 8 Mg DM ha^{-1} yr^{-1} in the first rotation period, the considerable yield variation is due to heterogeneous site conditions and occasionally growth-limiting heavy metal concentrations in the topsoil
Yield expectation / biomass production at reclamation sites	cropping experiments and on-farm trials with pre-selected high-yielding clones, for example *Tordis* and *Inger*: <0.1 - 5 Mg DM ha^{-1} yr^{-1} in the first rotation period, yields primarily depending on the plant available water
Growing season	April to October
Soil requirements	tolerates a wide range of soils, undemanding with respect to nutrient supply (NPK), but claims a well-balanced water supply over the year, optimal growth pH 5.5 to 6.5
Phytoremediation & soil improvement	usable for phytoexctraction of heavy metals (Cd, Zn, Cu, Pb, Cr), phytovolatilisation and rhizodegradation of organic pollutants, hydraulic control, promoting humus formation by easily decomposable litter and intensive rooting
Growth limiting factors / cultivation risks	low plant available water capacity, summer drought, lowest yield potential on pure sands and humus poor raw soils, fungi (especially leaf rust) and sometimes insects
Agronomic features	low-input system, short to medium rotation, easy to manage with fully mechanised planting of cuttings, self-regenerating by sprouting
Irrigation	non-irrigated, irrigation technologically difficult and in general unprofitable, only in case of emergency in the planting year
Harvest	in SRC fully mechanised by modified maize choppers, dry matter content of wood chips 30 % (after drying)

(19) *Populus x spec.* (pure species and hybrids, pre-selected clones)

Common name	poplar, hybrid poplar, aspen, cottonwood
Class / type	fast-growing pioneer tree species
Typology	energy crop (burning, pyrolysis) and lignocellulosic crop / fuelwood in short-rotation coppices (SRC), plantations and forests, material utilisation
Native	northern temperate climate zone
Yield expectation / biomass production at sewage farms	first cropping experiments on disused irrigation fields: <0.1 - 8 Mg DM ha^{-1} yr^{-1} in the first rotation period, in general yields are corresponding to the water availability
Yield expectation / biomass production at reclamation sites	cropping experiments and on-farm trials with pre-selected high-yielding and drought tolerant clones, for example *Max 1*, *2*, *4*, *Androscogin*, *Hybrid 275*: <0.1 - 9 Mg DM ha^{-1} yr^{-1} in the first rotation period
Growing season	April to October
Soil requirements	rather undemanding, but needs a well-balanced water supply and moderate soil pH, highest biomass increment on well drained loamy soils to sufficiently aerated loam, optimal growth pH range 5.5 to 6.5
Phytoremediation & soil improvement	recommendable for the cleaning of moderately contaminated arable, "underutilised" or abandoned land, in particular rhizodegradation of organic pollutants and hydraulic control, soil conserving by intensive rooting and soil humus accumulation, erosion protection and additional CO_2 sequestration, minimal nutrient removal
Growth limiting factors / cultivation risks	low plant available water capacity, strong summer drought leads to growth depressions and irreversible vitality loss, low tolerance to heavy metals, sensitive to waterlogging and some insects and fungi
Agronomic features	low-input and self-sustaining system, short to medium rotation with ecological benefits, fully mechanised planting of cuttings, self-regenerating by sprouting
Irrigation	non-irrigated, permanent irrigation technology far beyond the break-even of profitability, only in case of emergency in the planting year
Harvest	in SRC fully mechanised by modified maize choppers or harvesters, dry matter content of wood chips 30 % (after drying)

(20) *Robinia pseudoacacia* L.

Common name	black locust, false acacia, *Robinia*
Class / type	fast-growing pioneer tree species, woody leguminous plant
Typology	high-quality timber and multipurpose energy (burning, pyrolysis), lignocellulosic and forage crop (high protein leaves)
Native	*Northern America*, worldwide grown from the subtropical to temperate zone, naturalised in *Berlin & Brandenburg* since 300 years
Yield expectation / biomass production at sewage farms	no reliable data, yield potential uncertain due to high dieback after planting, very sensitive to weed pressure in the start-up phase
Yield expectation / biomass production at reclamation sites	1 - 11 Mg DM ha^{-1} yr^{-1}, strongly depending on reclamation, stand and growth age, soil conditions (P and K availability), genotype and rotation period
Growing season	mid-May to October
Soil requirements	wide variety of soils, highest yields on well drained loamy soils with an optimum pH range between 5.5 and 6.5, sensitive to topsoil compaction and waterlogging, but high heavy metal and acid tolerance
Phytoremediation & soil improvement	soil improving by assimilation of atmospheric nitrogen (symbiotic *Rhizobia*) and intensive rooting, permanent vegetation cover minimizes seepage water formation and leaching of contaminants, promotes soil humus accumulation by additional CO_2 sequestration
Growth limiting factors / cultivation risks	very sensitive to late frost, needs a good phosphorous and potassium supply, especially on sewage farms predisposed to fungal diseases (*Fusarium, Phomopsis*), higher acid and heavy metal tolerance as compared to willow and poplar
Agronomic features	well-established in reclamation of mine soils and in the reutilisation of abandoned land, easy propagation by seedlings and root-sprouts, fully mechanised planting, if once established self-regenerating
Irrigation	highest drought and heat resistance of all cultivated trees in the region, thus irrigation would be inefficient, irrigation only in the case of emergency during the planting year
Harvest	in SRC fully mechanised by modified maize choppers, logging with (forestry) harvesters, dry matter content of wood 30 % (after drying)

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ANNEX 2

"Spatial Database"

Overview of the available public spatial information for the case study area and source references

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TABLE 19: CLIMATIC DATASETS FOR THE CASE STUDY *GERMANY*, REFERENCE NUMBER LINKED TO TABLE 23

Description	Spatial extent	Spatial resolution	Reference date	Reference number
Multi-annual mean temperature	Germany	raster data, 1 km	1981-2010	1.1
Multi-annual min temperature	Germany	raster data, 1 km	1981-2010	1.2
Multi-annual water balance	Germany	raster data, 1 km	1971-2000	1.3
Multi-annual grids of potential evapotranspiration over grass	Germany	raster data, 1 km	1981-2010	1.4
Multi-annual number of frost days	Germany	raster data, 1 km	1981-2010	1.5
Multi-annual number of ice days	Germany	raster data, 1 km	1981-2010	1.6
Multi-annual precipitation	Germany	raster data, 1 km	1981-2010	1.7
Multi-annual grids of soil moisture in 5 cm depth under grass and sandy loam	Germany	raster data, 1 km	1991-2010	1.8
Multi-annual grids of vegetation begin	Germany	raster data, 1 km	1992-2015	1.9
Multi-annual grids of vegetation end	Germany	raster data, 1 km	1992-2015	1.10

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TABLE 20: SOIL DATASETS FOR THE CASE STUDY GERMANY, REFERENCE NUMBER LINKED TO TABLE 24

Description	Spatial extent	Spatial resolution	Reference date	Reference number
Soil type (topsoil)	Brandenburg	vector data, 1:300000	2007	2
Soil wetness condition	Brandenburg	vector data, 1:300000	2007	2
Water binding properties	Brandenburg	vector data, 1:300000	2007	2
Water movement characteristic	Brandenburg	vector data, 1:300000	2007	2
Agricultural yield potential	Brandenburg	vector data, 1:300000	2007	2
Derivations of digital elevation model	Brandenburg	vector data, 1:300000	2007	2
Medium scale historical agricultural map	Brandenburg	vector data, 1:100000	2007	2

TABLE 21: NATURE CONSERVATION DATASETS FOR THE CASE STUDY *GERMANY*, REFERENCE NUMBER LINKED TO TABLE 24

Description	Spatial extent	Spatial resolution	Reference date	Reference number
Nature conservation area (borders)	Brandenburg	vector data, 1:10000	2016	3
Landscape conservation area (borders)	Brandenburg	vector data, 1:10000	2016	3
Large-scale protected area (borders)	Brandenburg	vector data, 1:10000	2016	3
FFH area (borders)	Brandenburg	vector data, 1:10000	2014	3
Bird reserve (borders)	Brandenburg	vector data, 1:10000	2014	3
Sensitive moor/fen areas (borders)	Brandenburg	vector data, 1:10000	2008	3
Borders of habitat types inclusive selected thematic information	Brandenburg	vector data, 1:100000	2016	3

TABLE 22: LAND USE DATASETS, TOPOGRAPHIC MAPS & DIGITAL ELEVATION MODELS FOR THE CASE STUDY *GERMANY*, REFERENCE NUMBER LINKED TO TABLE 24

Description	Spatial extent	Spatial resolution	Reference date	Reference number
CORINE Land Cover (10 ha)	Germany	vector data 1:100000	2012	4.1
Biotope and land use classification	Brandenburg	vector data 1:10000	2009	3
Digital landscape model	Germany	vector data 1:250000	2006-2015	4.2
Digital topographic map	Germany	vector data 1:200000	2006-2015	4.3
Digital elevation model	Germany	raster data, ca. 200 m	2002-2013	4.4
Digital elevation model, processed SRTM data (version 4.1)	East Germany	raster data, ca. 90 m	2000	5

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TABLE 23: DATA OWNERS AND SOURCES, PART I

Reference number	Data owner	Source
1.1	Deutscher Wetterdienst (DWD)	ftp://ftp-cdc.dwd.de/pub/CDC/grids_germany/multi_annual/air_temperature_mean/
1.2	Deutscher Wetterdienst (DWD)	ftp://ftp-cdc.dwd.de/pub/CDC/grids_germany/multi_annual/air_temperature_min/
1.3	Deutscher Wetterdienst (DWD)	ftp://ftp-cdc.dwd.de/pub/CDC/grids_germany/multi_annual/water_balance/
1.4	Deutscher Wetterdienst (DWD)	ftp://ftp-cdc.dwd.de/pub/CDC/grids_germany/multi_annual/evapo_p/
1.5	Deutscher Wetterdienst (DWD)	ftp://ftp-cdc.dwd.de/pub/CDC/grids_germany/multi_annual/frost_days/
1.6	Deutscher Wetterdienst (DWD)	ftp://ftp-cdc.dwd.de/pub/CDC/grids_germany/multi_annual/ice_days/
1.7	Deutscher Wetterdienst (DWD)	ftp://ftp-cdc.dwd.de/pub/CDC/grids_germany/multi_annual/precipitation
1.8	Deutscher Wetterdienst (DWD)	ftp://ftp-cdc.dwd.de/pub/CDC/grids_germany/multi_annual/soil_moist/
1.9	Deutscher Wetterdienst (DWD)	ftp://ftp-cdc.dwd.de/pub/CDC/grids_germany/multi_annual/vegetation_begin/
1.10	Deutscher Wetterdienst (DWD)	ftp://ftp-cdc.dwd.de/pub/CDC/grids_germany/multi_annual/vegetation_end/

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TABLE 24: DATA OWNERS AND SOURCES, PART II

Reference number	Data owner	Source
2	Landesamt für Bergbau, Geologie und Rohstoffe Brandenburg (LBGR)	ordered online & delivered by DVD (fee required)
3	Landesamt für Umwelt Brandenburg (LfU)	http://www.metaver.de/search/dls/service/AC198EC3-DAE6-4F8F-9FF6-62375FCEF7C6
4.1	Bundesamt für Kartographie und Geodäsie	http://www.geodatenzentrum.de/geodaten/gdz_rahmen.gdz_div?gdz_spr=deu&gdz_akt_zeile=5&gdz_anz_zeile=1&gdz_unt_zeile=22&gdz_user_id=0
4.2	Bundesamt für Kartographie und Geodäsie	http://www.geodatenzentrum.de/geodaten/gdz_rahmen.gdz_div?gdz_spr=deu&gdz_akt_zeile=5&gdz_anz_zeile=1&gdz_unt_zeile=1&gdz_user_id=0
4.3	Bundesamt für Kartographie und Geodäsie	http://www.geodatenzentrum.de/geodaten/gdz_rahmen.gdz_div?gdz_spr=deu&gdz_akt_zeile=5&gdz_anz_zeile=1&gdz_unt_zeile=5&gdz_user_id=0
4.4	Bundesamt für Kartographie und Geodäsie	http://www.geodatenzentrum.de/geodaten/gdz_rahmen.gdz_div?gdz_spr=deu&gdz_akt_zeile=5&gdz_anz_zeile=1&gdz_unt_zeile=3&gdz_user_id=0
5	International Centre for Tropical Agriculture (CIAT), NASA	http://srtm.csi.cgiar.org/SELECTION/inputCoord.asp