COLLÈGE DE FRANCE 1530

Renewable Carbon for a renewed chemistry

Paul COLONNA

INRA SCIENCE & IMPACT

INRA: a 10-year strategy implemented…

8 211 permanent staff

839 M€ budget In 2012

…by 13 research divisions

ALIMH	Nutrition, Chemical Food Safety & Consumer Behavior
BAP	Plant Biology and Breeding
CEPIA	Science & Process Engineering of Agricultural Products
EFPA	Forest, Grassland & Freshwater Ecology
EA	Environment & Agronomy
GA	Animal Genetics
MIA	Applied Mathematics & informatics
MICA	Microbiology & the Food Chain
PHASE	Animal Physiology & Livestock Systems
SA	Animal Health
SPE	Plant Health & Environment
SAD	Science for Action & Sustainable Development
SAE2	Social Sciences, Agriculture & Food, Rural Development & Environment

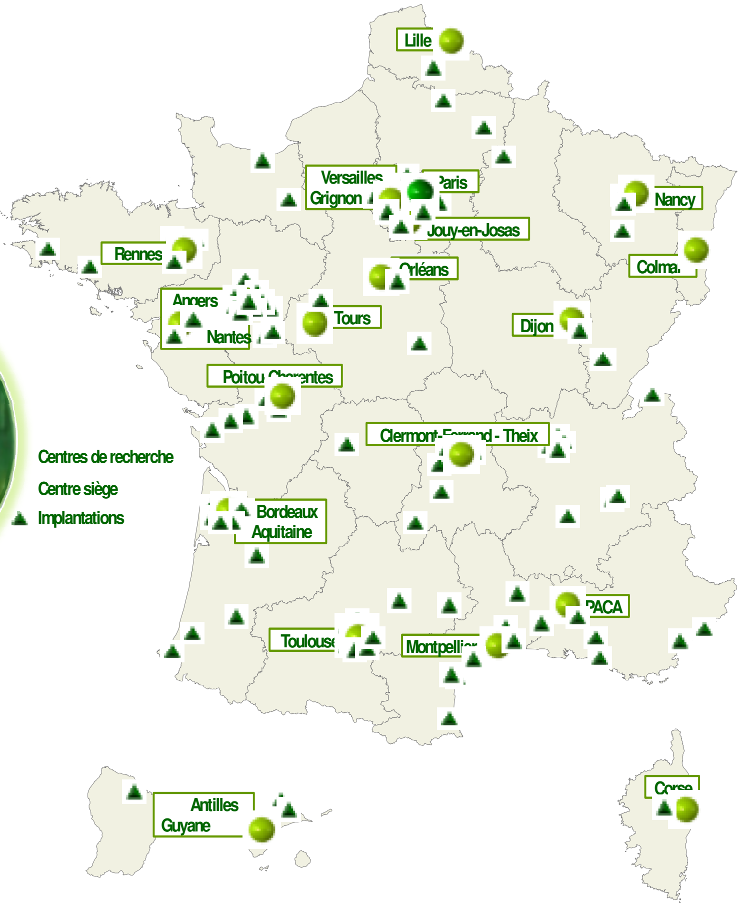
2,500 researchers

200 research units

49 experimental units

± 1,800 PhD students in the labs

…across 17 research centers



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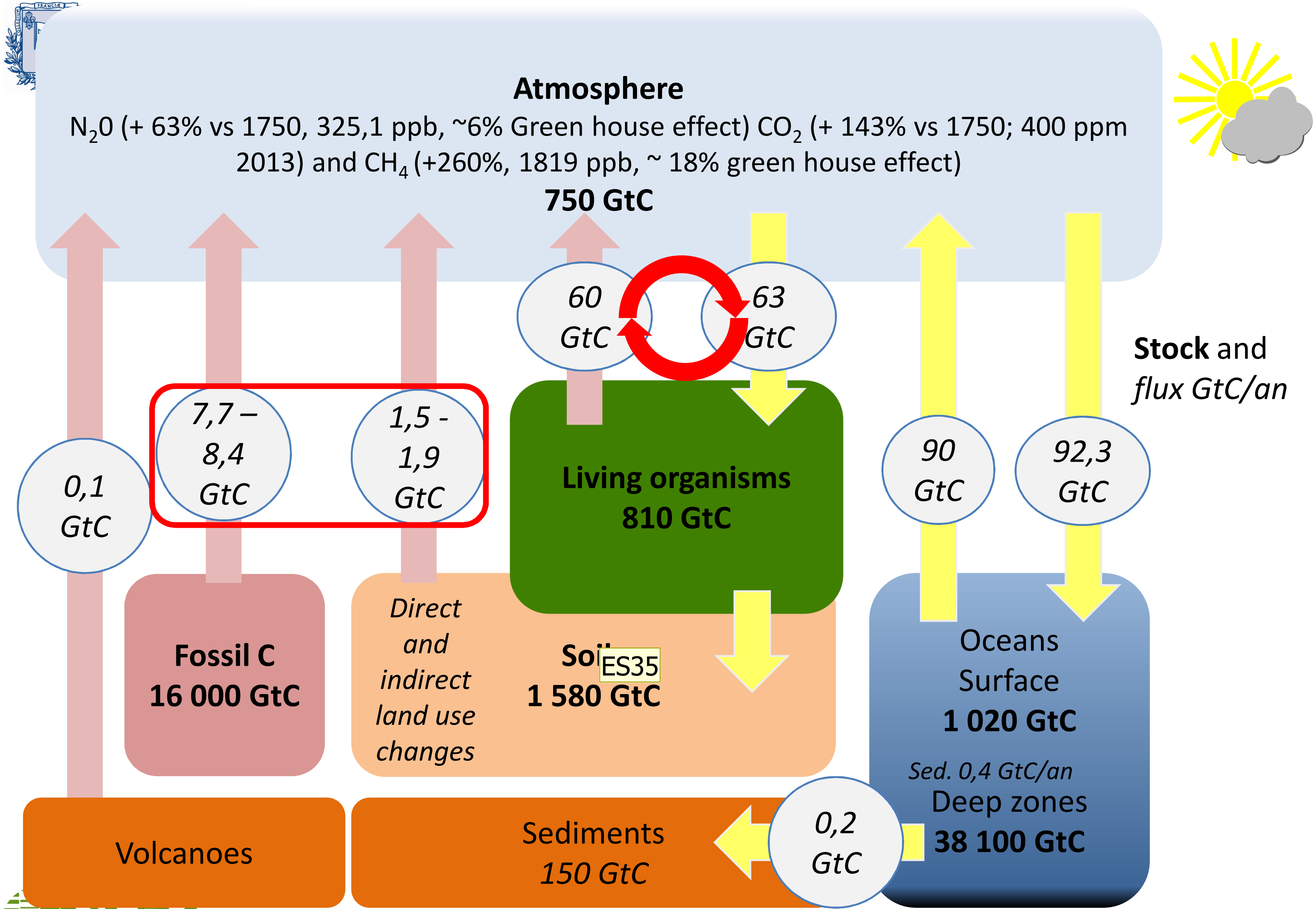


Sources: GIEC, Friedlenstein et al., 2010; Pan et al., 2011; OMM 2013

ES35 "usage"

Elodie SALICETO, 11/05/2012

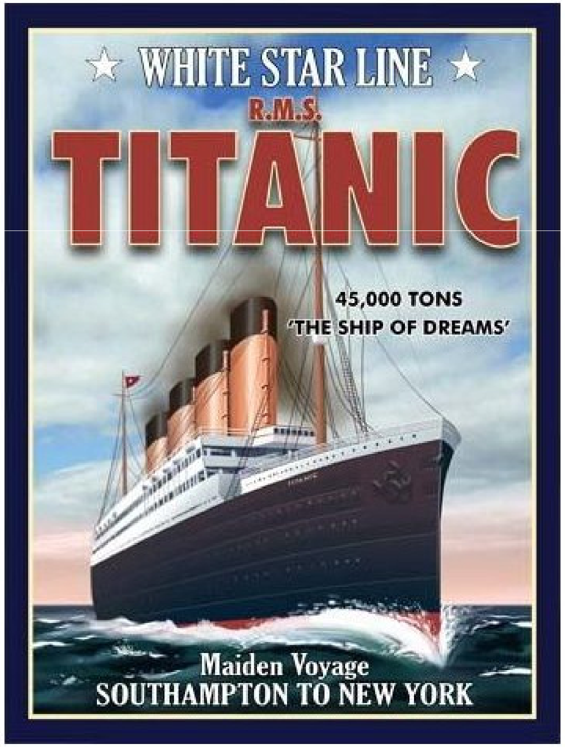
Primary production of renewable energy

Countries	Share of renewables in gross energy consumption (%)	Ren primary prod. (Mteo)	Solar (%)	Biomass and wastes (%)	Geothermal energy (%)	Hydraulic energy (%)	Wind energy (%)
UE-27	**9.0**	148.4	1.7	**67.7**	3.9	19.0	7.7
Germany	8.5	27.7	3.5	**77.0**	1.7	5.8	12.0
Spain	9.3	11.9	5.7	**47.9**	0.1	19.0	27.3
France	7.5	19.6	0.3	**70.2**	0.6	25.1	3.5
Italy	9.5	14.7	1.0	**34.0**	32.6	28.7	3.8
Netherlands	3.9	2.8	0.9	**84.4**	0.1	0.3	14.2
Austria	**27.3**	8.4	1.5	**54.6**	0.4	**41.5**	2.0
Finland	**23.2**	7.8	0.0	**85.6**		13.9	0.3
Sweden	**34.4**	15.9	0.1	**62.8**	-	**35.8**	1.4
UK	3.0	5.1	1.4	**74.1**	-	8.9	15.7
Norway	**42.4**	12.1	-	9.7	-	**89.6**	0.7

Source: Eurostat, 2009

This situation is not sustainable

- It does not meet the needs of today's society, since it can not be extended to the entire globe due to resource limitations, impacts on the environment and health (particular case of foods in Western countries).
- It affects future generations, by irresistible exhaustion of fossil carbon whose reserves are limited in principle.
- The enrichment of CO_2 in the atmosphere leads to a strengthening of the greenhouse effect.
- Organic carbon during decomposition in the soil can be removed from storage quickly in response to changes in agricultural practices, deforestation, thus enhancing the greenhouse effect.
- The excess demand (development) is currently conducting to tensions between yields surfaces and ecosystems' capacity to provide simultaneous and non-market goods (ecosystem services).



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Our societies are facing four challenges

- (1) meet the food needs of a global population of some 9.7 billion people in 2050* (7.1 in 2013), including some regional populations experiencing strong economic growth,
- (2) control, limit and reduce emissions of greenhouse gases (GHGs) in the atmosphere to yield a neutral development (emission = absorption) carbon plan reduction commitment by two of GHG emissions 2050 compared to 1990 (factor 4 in France).
- (3) develop substitutes for fossil fuels (and their derivatives) which reserves for a given cost, will be increasingly scarce. Uses in chemistry represent only 9 % of the uses of oil and gas in France.
- (4) expand the range of molecules and materials available to prevent human and environmental health risks associated with chemical substances, which are necessary to our needs in terms of clothing, transportation, housing and hygiene.

*source : INED

Scenario of sustainable development

1972 United Nations Conference on the Human Environment, Stockholm

1987 Commission Brundtland

1992 Earth Summit in Rio

2002, World Summit on Sustainable Development,Johannesburg

2009, Copenhagen World Summit

RIO+20 the future we want

1970 1980 1990 2000

Club de Rome: The limits to growth

Convention Climat

Green Chemistry

Kyoto Protocol: reduce GHG emissions to an average of 5% againt 1990 levels

Sustainable development *is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*

CSR Corporate Social Responsibility

Bioeconomie *with biotechnologies as game changers.*

Low sustainability ?

The challenge of a green economy is to improve the standard of living in developing countries without increasing their carbon footprint and at the same time maintain the standard of living in developed countries while reducing their footprint.

Bioeconomy: a shared vision ?

OCDE

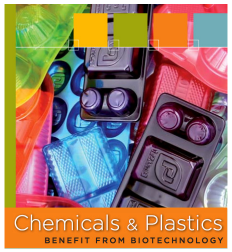
Europe

Germany

中华人民共和国科学技术部
Ministry of Science and Technology of the People's Republic of China

China included the bioeconomy and biotech sector as priorities within its 12th five-year economic guideline, from 2011 to 2015

Australian Government
Department of Industry



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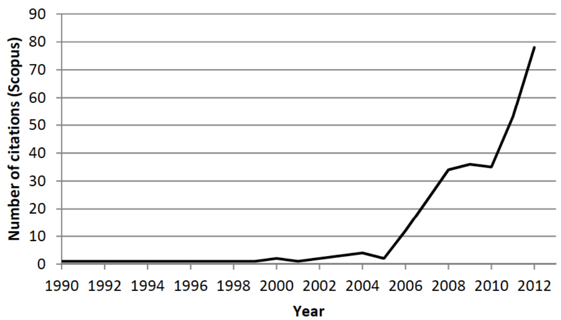
Base Scopus



Source: Staffas, 2013

From Biobased–economy to Bio-economy

- ~~Greenwashing~~
- Extended applications of modern biology,

the myth of Prometheus, Opportunities: GMO, up to synthetic biology,	***Biologizing* agriculture (production) and industry (transformation)**

- Laws of diminishing returns !!

- Systems biology
- Systemic approach: understanding the relationships between technologies, modelling and simulation capacities at different scales
⇒Integrated value chain approach

- New and performant products to drive market development

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Who	When	document	source	Bio-based ou bioeconomy	Vision P ou T	Targets	Main domains
OCDE	2009	The bioeconomy to 2030: designing a policy agenda	OCDE	BE	T	No	Biotechnology, agriculture, health and industry
UE	2012	Innovating for sustainable growth: a bioeconomy for Europe	Commission	**BBE**	P & T	economical	Foods, resources, chimistry, innovation and skills
USA	2012	National Blueeconomy Blueprint	White house	BE	P	+, qualitative	biotechnologies
Canada	2009	The Canadian blueprint: beyond moose and moutains	Biotech Canada	BE	P	+, qualitative	biotechnologies
Germany	2011	National Research Strategy	Germ.Min. Research	**BBE**	P	+, qualitative	Agriculture, health, food and bioenergies
Finland	2011	Distibuted bio-based economy: driving sustainable growth	S. Res. Council (Formas)	**BBE**	T	+, qualitative	Sustainable uses of resources and biorefineries
Sweden	2012	Swedish Research and innovation: strategy for a bio-based economy	ACIL Taiman	BE	T	no	Sustainable uses of resources

For INRA

Territories

- Lands and ressources
  - Location and actors: agro-industrial ecology
  - Rules for allocation
- Sustainability assessment

- *Adaptation to climate change*
- *Mitigation of climate change*
- *Competition with urban growth*

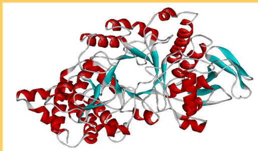
Phototrophic system

- Annual, perennial plantes, forests, micro-algae
  - Green biotechnologies
  - New species, Phytoremediation
- Cropping systems

Exert pressure on the expansion of the bioeconomy system

Biorefinery: land, harbor and environmental

- Fractionation technologies
- Separation technologies
- Transformation technologies
  - Industrial biotechnologies , synthetic biology
  - Nanobiotechnologies



Economics of innovation , public policies, regulations

Ecoconception

Ingredients, additives

Foods

Energies

Nanobio-objects
Platform molecules with reactivity or property value uses (clothing, housing, transportation, health ...

Enzymes, Microorganisms, Agents tech

Ecosystem services (support, control, socio-cultural

A biorefinery is a facility that integrates biomass conversion processes and equipment to produce foods, fibers, fuels, power and value-added chemicals

Agricultural, algal and forestry **biomasses**

Grain, stem

1st g

starch, fibers, lipids, gluten

2nd g

Polysaccharides, fatty acids, Protein isolates**, sugar**

3rd g

Fatty acids, glycerol, hexoses, pentose, polypepides

4th g

Syngas, CO, H_2

Physical processes

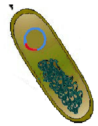
Chemical processes

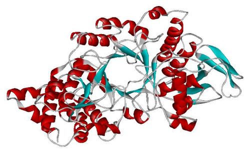
Biotechnologies

Thermo-mechanical processes

Foods, Bioenergies,
Biomaterials,
Bio-based chemicals

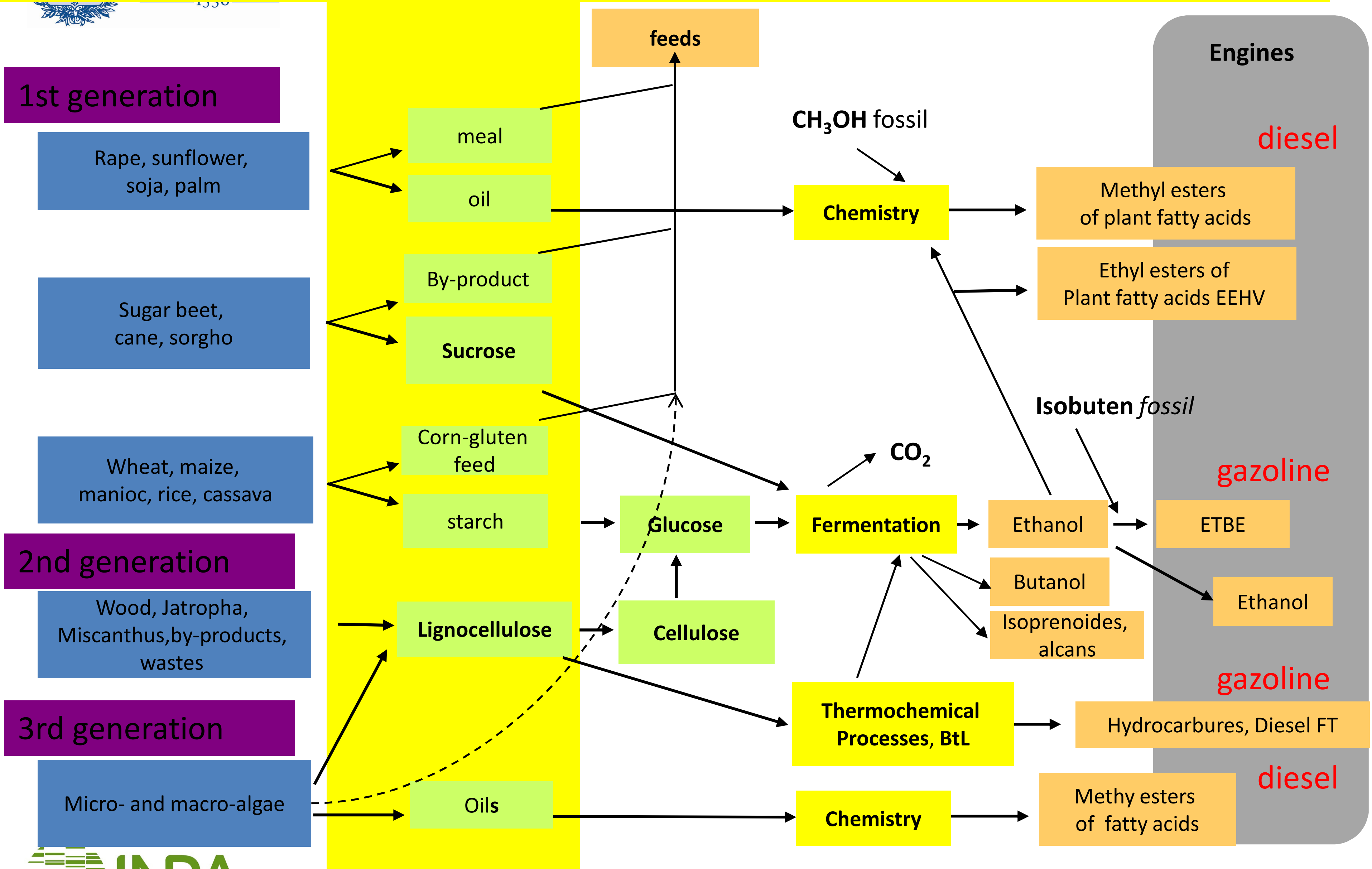
Molecules or assemblies with functional/nutritional properties





Basic units (reactivity)

A biorefinery is a facility that integrates biomass conversion processes and equipment to produce foods, fibers, fuels, power and value-added chemicals



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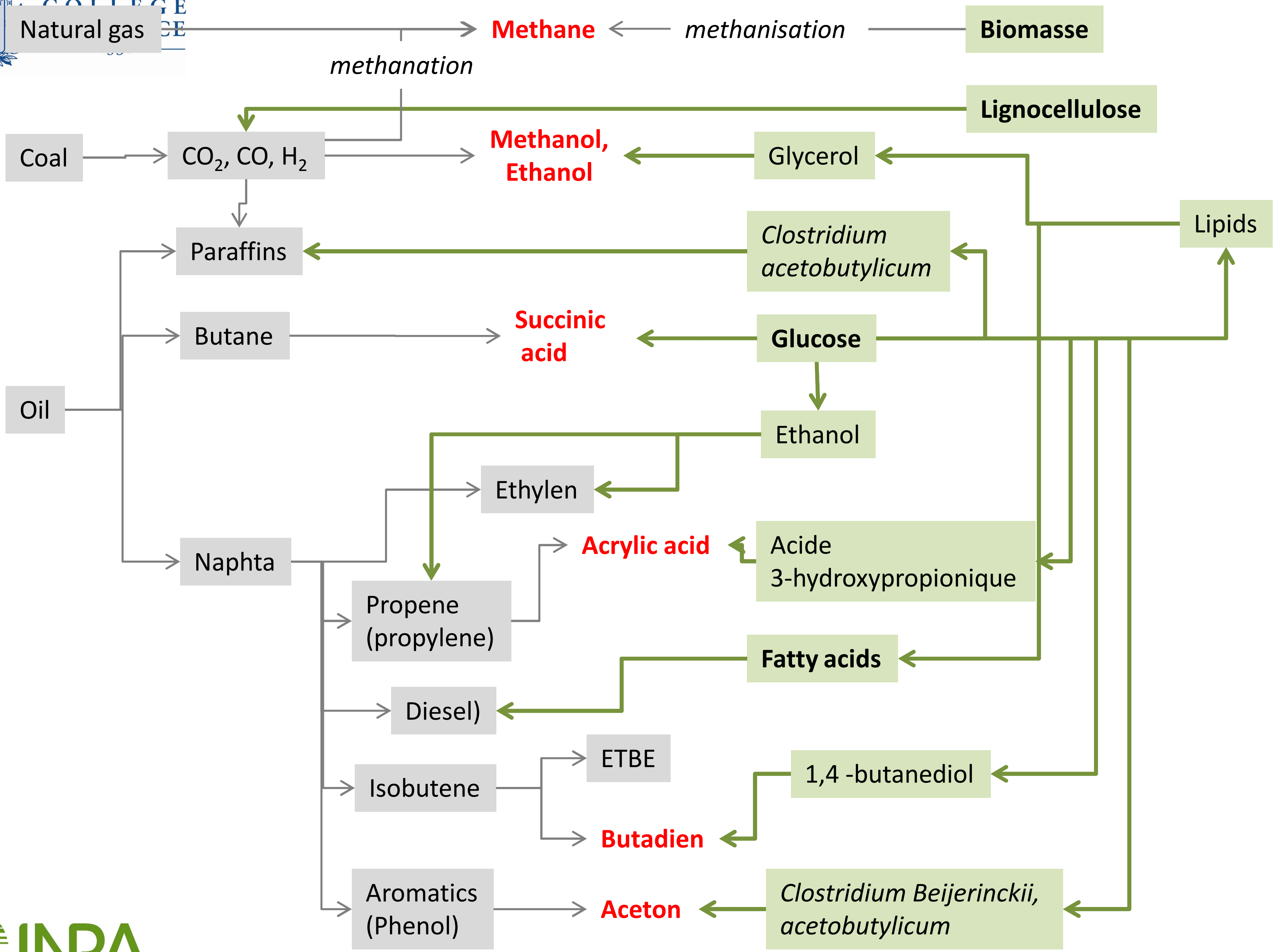
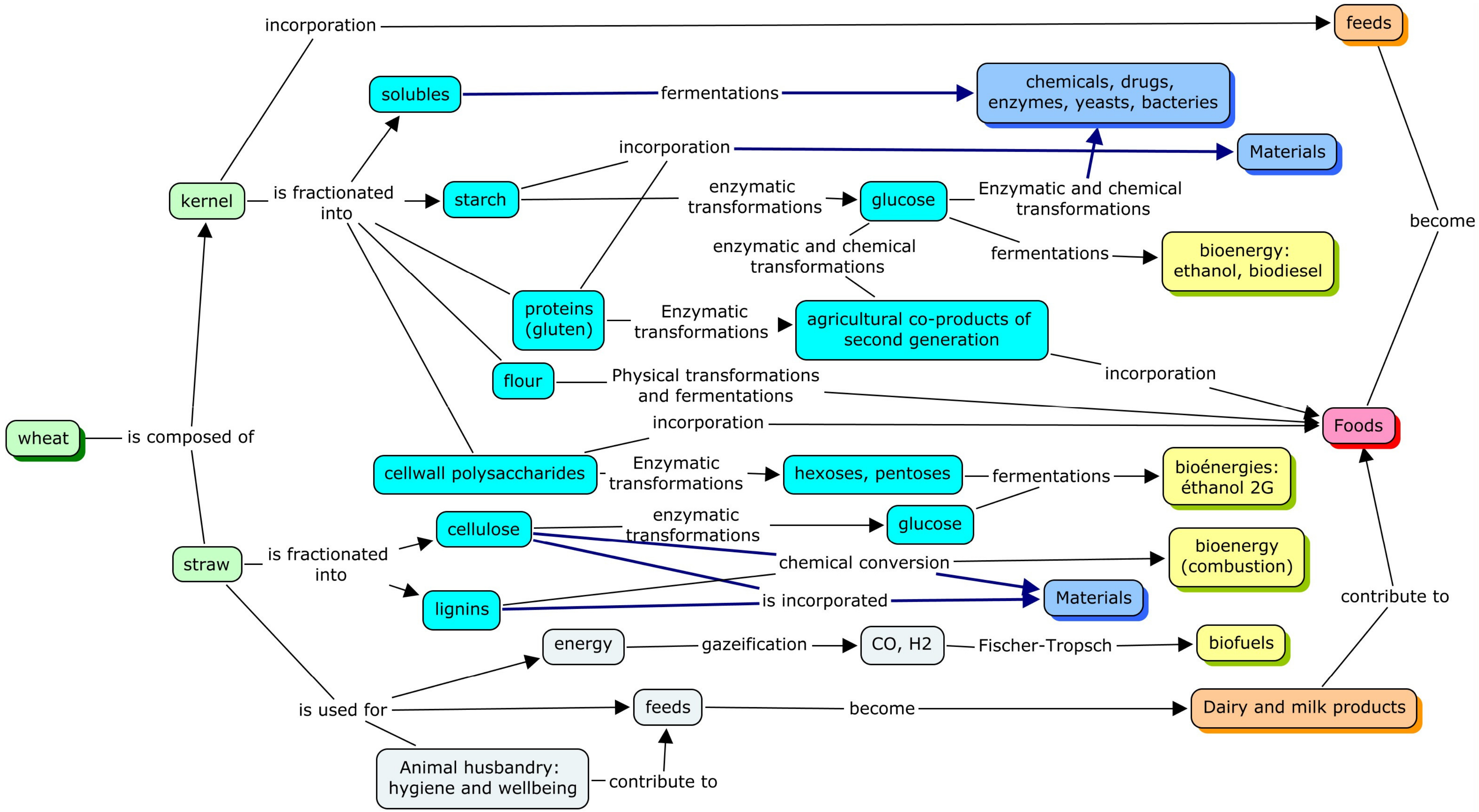
Common features

- biotechnology from biodiversity systems biology to synthetic biology and integrative biology (crossing of food, energy systems, chemical).
- Systemic approach

Two complementary visions:

- Bio-Based Economy: a scientific and economic strategy to create the conditions for a transition from an economy based on fossil fuels to one based on biological raw materials (economic growth efficient economy in harmony with the environment and economy adopted by the citizen-consumer). Biotechnology are then elements of technological breakthrough in our socio-ecosystems. The bio-economy is the operational arm of sustainable development, in synergy with the evolution scenarios based on sobriety for so-called developed societies.
- BioEconomy: sustainable growth through advances in the biosciences to the "*biologization*" industrial processes and products, with the development of environmental technologies and wastes reduction.


Natural gas
Methane
methanisation
Biomasse
methanation
Lignocellulose
Coal
CO_2, CO, H_2
Methanol,
Ethanol
Glycerol
Lipids
Paraffins
Clostridium
acetobutylicum
Butane
Succinic
acid
Glucose
Oil
Ethanol
Ethylen
Naphta
Acrylic acid
Acide
3-hydroxypropionique
Propene
(propylene)
Fatty acids
Diesel)
ETBE
1,4 -butanediol
Isobutene
Butadien
Aromatics
(Phenol)
Aceton
Clostridium Beijerinckii,
acetobutylicum

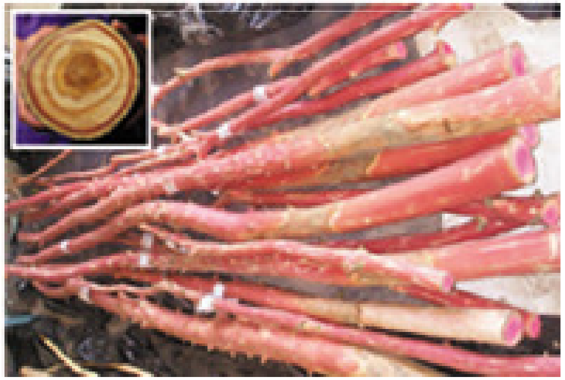


wheat
is composed of
kernel
straw
incorporation
feeds
is fractionated into
solubles
fermentations
chemicals, drugs, enzymes, yeasts, bacteries
starch
incorporation
Materials
enzymatic transformations
glucose
Enzymatic and chemical transformations
become
enzymatic and chemical transformations
fermentations
bioenergy: ethanol, biodiesel
proteins (gluten)
Enzymatic transformations
agricultural co-products of second generation
incorporation
flour
Physical transformations and fermentations
Foods
incorporation
cellwall polysaccharides
Enzymatic transformations
hexoses, pentoses
fermentations
bioénergies: éthanol 2G
is fractionated into
cellulose
enzymatic transformations
glucose
chemical conversion
bioenergy (combustion)
lignins
is incorporated
Materials
contribute to
energy
gazeification
CO, H2
Fischer-Tropsch
biofuels
is used for
feeds
become
Dairy and milk products
Animal husbandry: hygiene and wellbeing
contribute to

The second new frontier : lignocellulose





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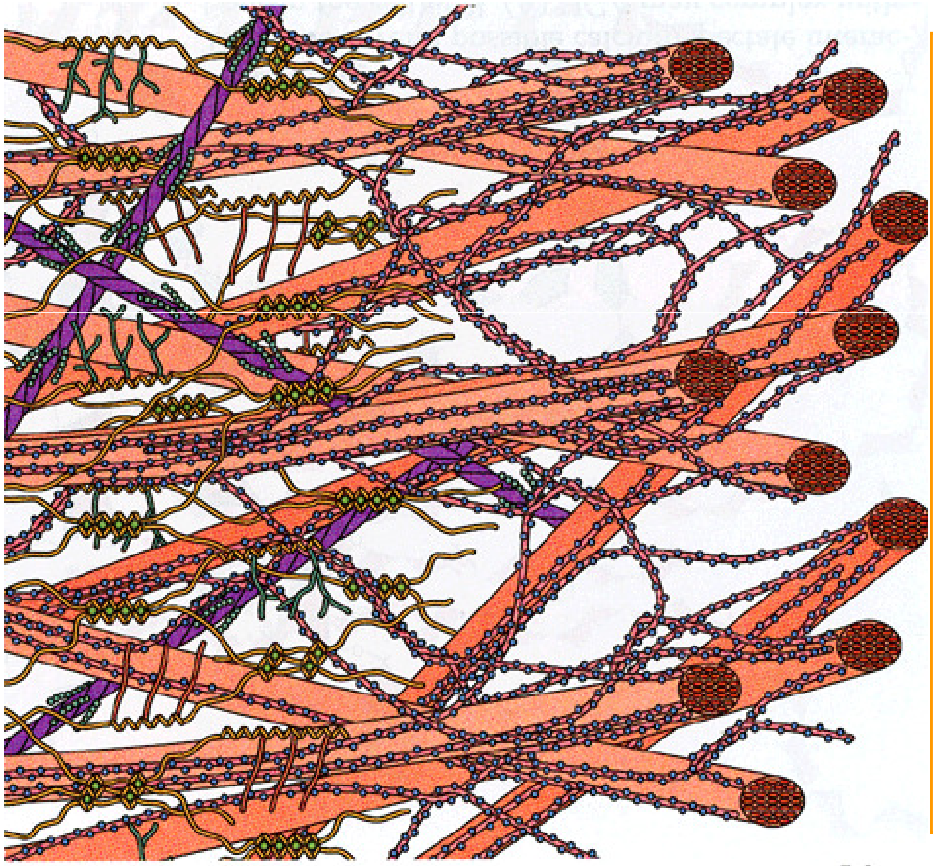
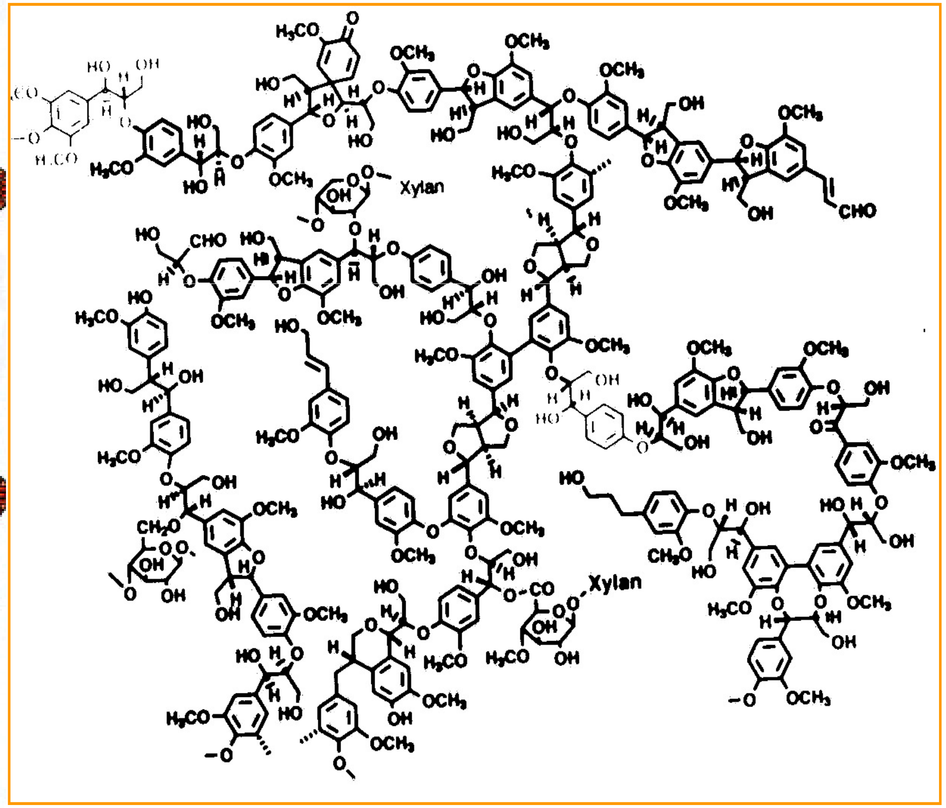
Cellulosic chains are entrapped in a tridimensional matrix of hemicelluloses and pectins, with a covalent network of lignins.





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Ligno-cellulose = substrat complexe

%	Celluloses	Hemi-celluloses	Lignins	Ashes
Wheat straw	51-54	26-30	16-18	7-8
Kénaf	55-59	23-25	12-15	2-5
Hard wood	38-49	19-26	23-30	1
Soft wood	40-45	7-14	26-34	1

Glucose (C6)

Phényl-propane units polymerized

Arabino-glucurono-xylanes (cereals)

Galacto-gluco-mannanes (softwoods)

Glucurono-xylanes (hardwoods)

Homogalacturonanes (pectines, P I)

C5 > C6

Scales

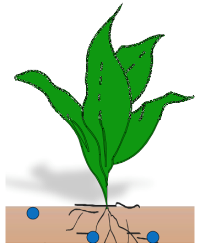
Reducing green house gaz emissions

Protecting ecosystemic services

Earth

Forests vs
Fields vs
Protected landscapes
Vs urban zones

field



Chloroplast

Game changers

Climate change

Land uses changes

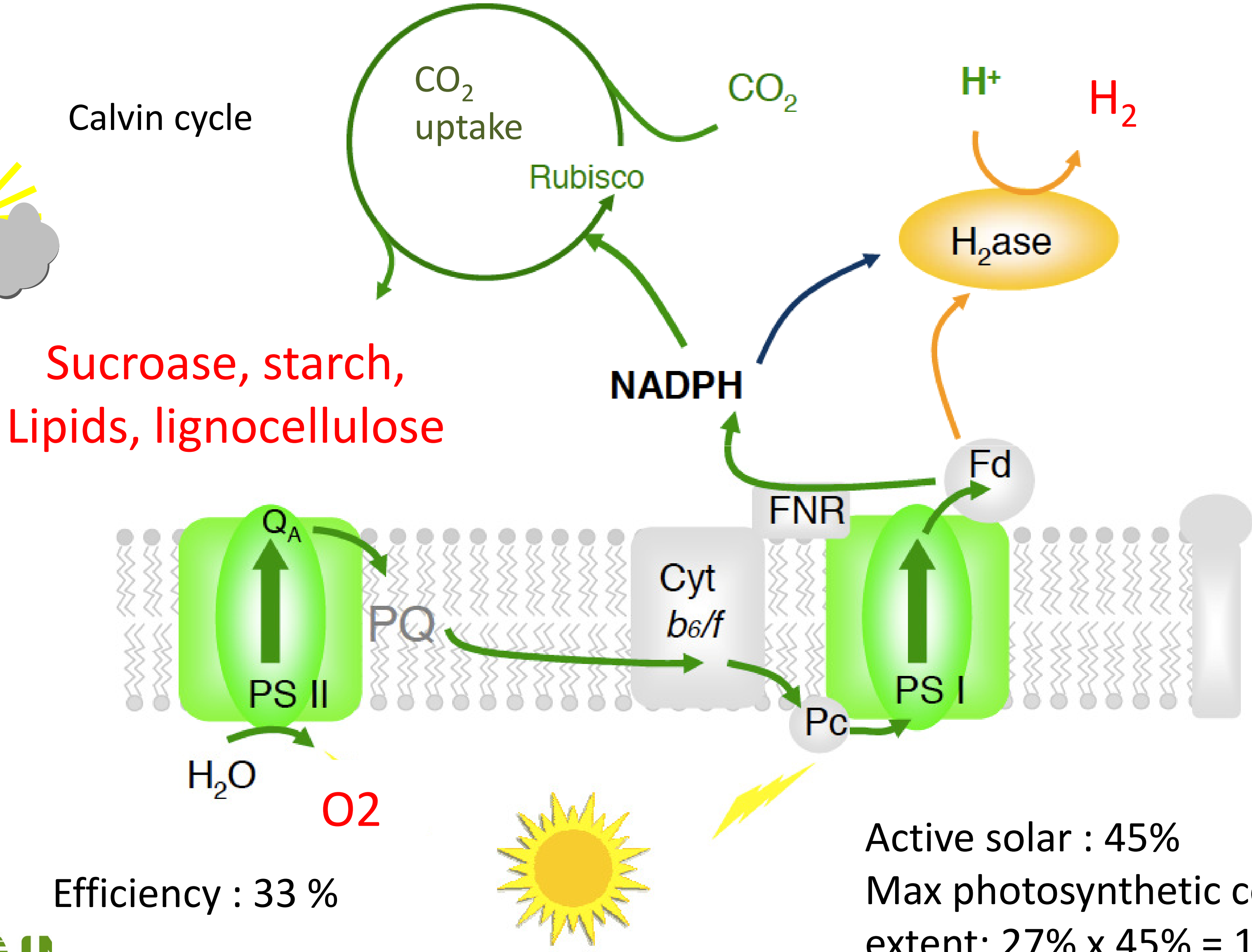
Agroecology

Species and cultivars

Green biotechnologies

Reversibility

Photosynthesis – carbon reactions



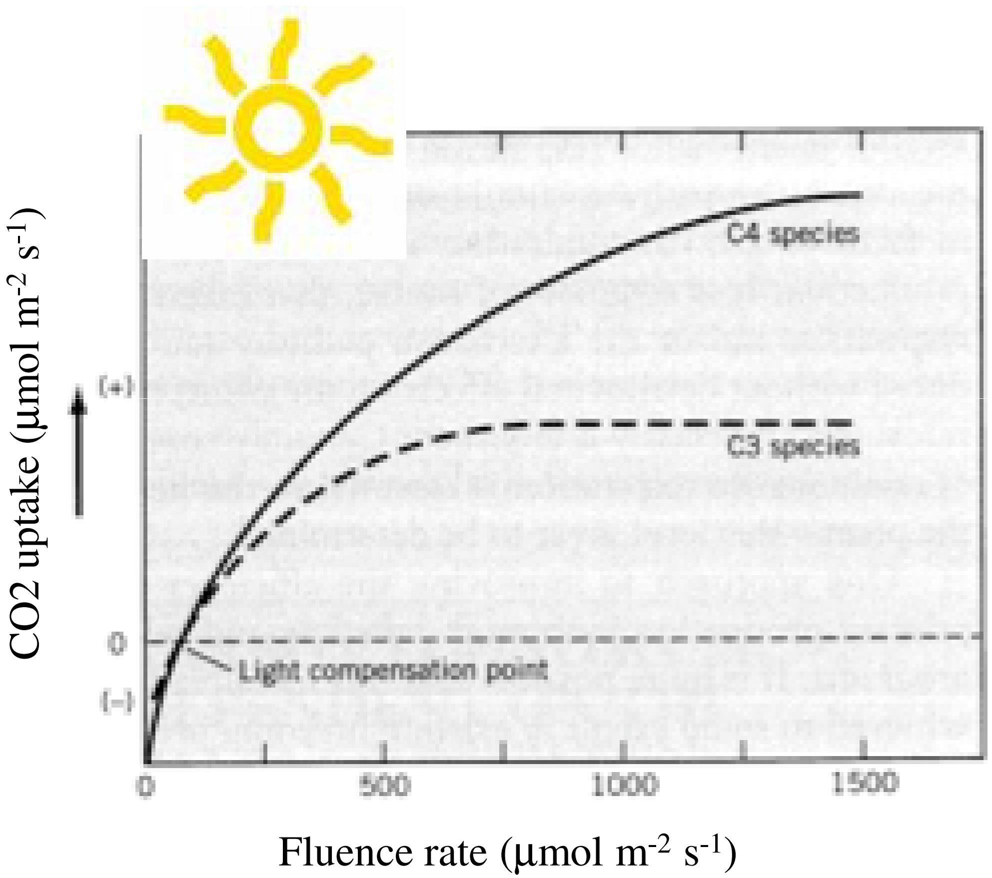
Efficiency : 33 %

Active solar : 45%
Max photosynthetic conversion extent: 27% x 45% = 15 %

Source: Blakenship et al., 2011

Light response curves for

- C3 (P-glycerate; most plants, including trees)
- C4 plant (oxalate; maize, canne, sorgho, miscanthus)



- CO_2 supply limits P/S in C3 plants
  - Light saturation occurs at fluence rates ~ 25% full sunlight
- CO_2 does not limit P/S in C4 plants AND
- C4 plants have a higher photosynthetic capacity
  - C4 plants concentrate CO2
  - C4 plants can take advantage of excess light and don't show light saturation
  - Utilization of excess light NRG allows C4 plants to provide the ATP needed to run the CO_2 pump

Climate change

Choice of biological factory
yield (t/ha.year)

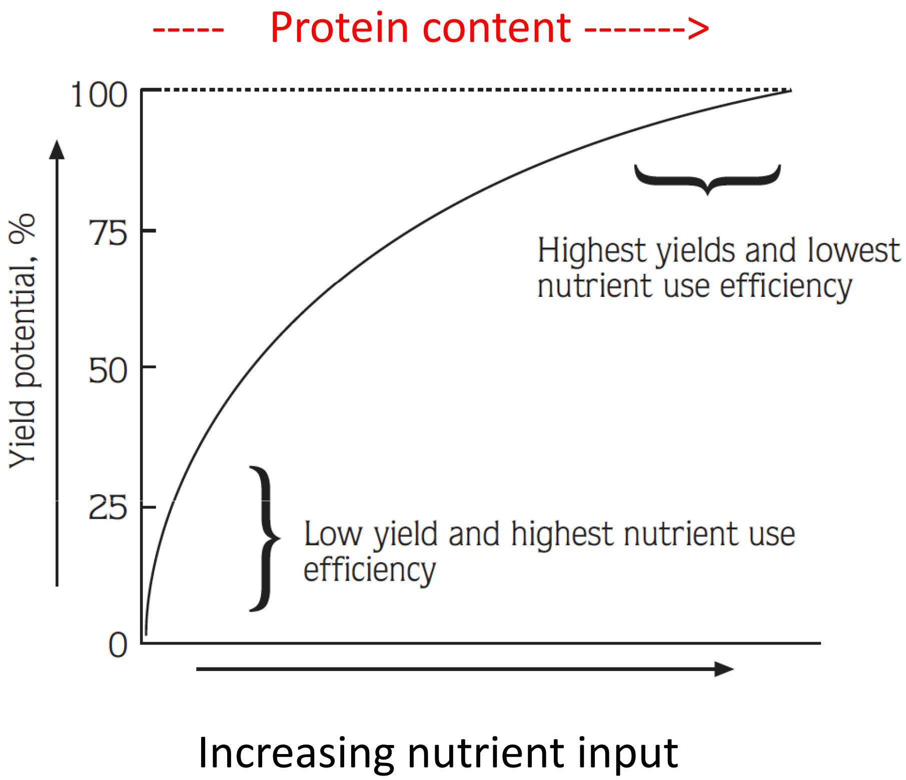
Organism	Oil	Sugars	Lignocellulose
Microalgae	25-60		
Lignocellulosic plants			**20-25**
Sugar canne, sugar beet		**10 - 13**	
Cereals		**9 - 12**	
Rape, sunflower, Soja	0.5- 2		
Palm	5-7		

Chemistry

Chemistry and materials

Chemistry and materials

Agroecology



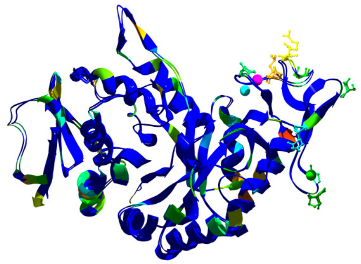
From Dibb, 2000

Rationale: by understanding ecological relationships and processes, agroecosystems can be **manipulated** to **improve** production and to produce more sustainably, with fewer negative environmental or social impacts and fewer external inputs.

=> **Design cropping systems that mimic nature, optimal use can be made of sunlight, soil nutrients and rainfall**

- ⇒ Crop diversity
- ⇒ Supply chain dependant on territories
- ⇒ Lignocellulosic crops from woodlots and hedges

Les enzymes: l'évolution qualitative



Enzymes des espèces Sauvages
4585 enzymes
MACiE database

Mutagénèse aléatoire, puis dirigée
10 à 20 variants ciblés à partir de données structurales

Accès aux gènes

Evolution moléculaire
Données structurales non nécessaires, Accumulation de modifications bénéfiques

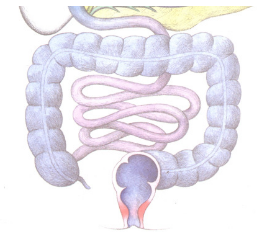
Arnold, 1997

Souches extrémophiles

Conception rationnelle
Modélisation, screening virtuel

Baker, 2008

Approche combinant les 4 précédentes



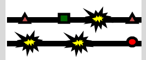
Métagénomique
10^5 à 10^6 clones par banque sans culture préalable

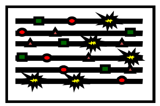
Amylase
(Payen, 1833)

Smith, 1978

Technology -push

Mutagénèse massive

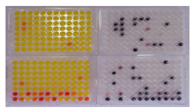




10^5-

Criblage à haut débit

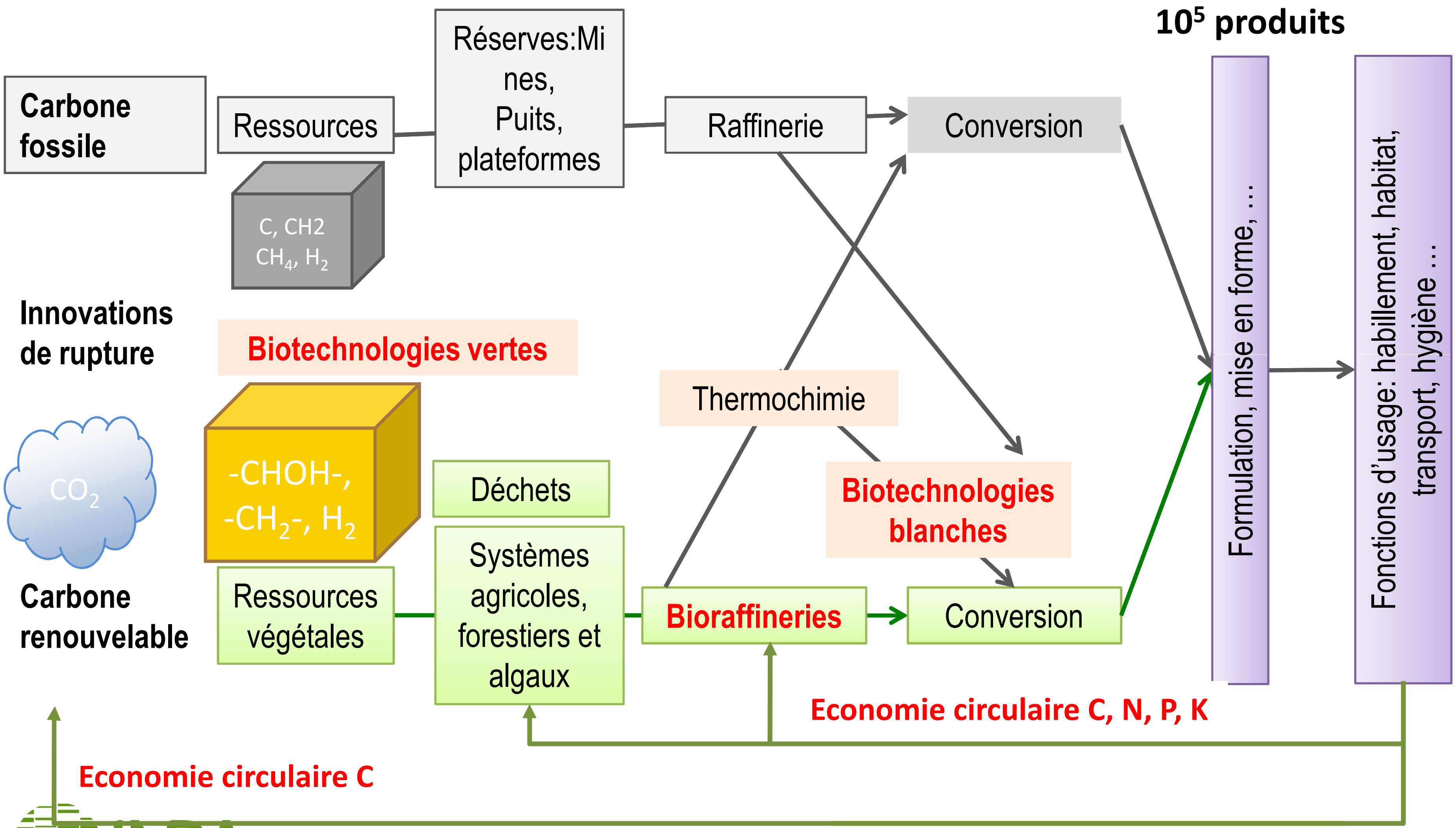
10^4-
10^5



Screening assays
10^3-

A partir de Monsan (2010)

Le couplage avec la chimie de synthèse



C as an energy carrier

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Hydrogen 119.4 MJ/Kg

50 — 50.1: Methane (O/C:0)

44 .5: Isoprenoïdes

44.0 : Microbial alcans

42.8: Diesel (O/C:0)

42.5: Gasoline (O/C:0)

40

36.3: FAME (O/C:0.17)

36.3: ETBE (O/C:0.17)

Industrial Biotechnologies

34.4: Butanol (O/C:0.25)

30 — 30 : Ethanol

28.8: DME (O/C:0.5)

26.9: Ethanol (O/C: 0.5)

> 20 Pyrolysis oils

20

16 – 19 Biomass

14.2: Glucose (O/C:1)

10

0: CO_2 / H_2O — 0

MJ/kg

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Land : a key productive variable with strong regional differences

- Earth 13 10^9 ha
- Agriculture : 38 % (4,9 **10^9** ha)
  - **33 % (1,6 10^9) for annual and perennial plants, including 287 10^6 irrigated**
  - 66 % (3,2 billion) for meadows and permanent pastures
- Forests : 30 % (3,9 billion)
- Remaining surfaces would be difficult to use.

Losses of lands	**Surfaces (10^6 ha)**
Deforestation for cultivation, mainly food, and urbanization	580
Overgrazing of 20% of grasslands	680
Over-harvesting for timber, industrial wood, wood energy (firewood)	137
Crop management defective, leading to water erosion, salinization	550
Industrialization, urbanization of agricultural lands	19,5

Source: FAO , 2009

Dream or nigthmare

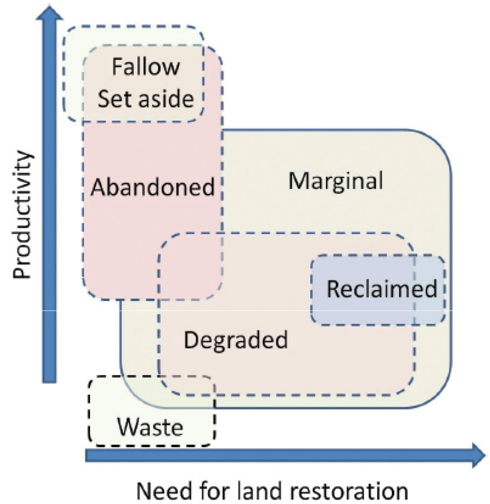
- All the products of plant biomass, of all types, including wood, just cover 1.19 billion toe / year, or 10.1% of the energy consumed worldwide. An important part of this renewable energy is consumed locally and escapes to the commercial channels. Biofuels account for 35 Mtoe / year.

- In EU countries, biomass used for energy (including combustion) in 2000 represented over 60% of total renewable energy consumed, with the bulk coming from wood or wastes and municipal solid waste : the weight of biofuels is almost negligible: 11 Mtoe / year.

- **Bioenergies can be part of the energy mix, without coping with all needs.**

Biomass availability

- Primary solid biomass use for heat and electricity will increase to ~ 160 Mtoe in 2020.
- Biofuels ~ 35 Mtoe: biodiesel 22 Mtoe, bioethanol 8 Mtoe, biomethane 0.7 Mtoe, biofuels from wastes 2,7 Mtoe
- Estimated target in 2020: bioelectricity 14%, biofuels 24%, bio-heat 62%.
- Estimated potential: 350 Mtoe (15EJ)
  - Studies EEA, BEE, European Forest sector outloook
- Main bottleneck: land
  - Availability: the production of 1 TWh using biomass demands a ground
  - area of 700 km^2
  - Logistics and transportation infrastructures



Dauber et al., 2012

- Biomass imports from third countries will increase, which may leads to higher sustainability risks
- Concerns about deforestation , forest certification requirements, concerns about 'carbon debt' issue, NGOs concerns
- National sustainability schemes are likely to have negative impacts on biomass trade and costs

World Consumption mondiale: 442 EJ/year
Share of bioenergies: 50 EJ/year
Potential 100 à 300 EJ/year. Chum et al., 2011

For the citizen – consumer

Food

- food technologies have reached a plateau of technological maturity,
- processes and the food system: which sustainability?

Bio-energy, bio-based molecules and bio-based materials

three possible complementary ways:

- Reproduction of original oil-based molecules;
- Production of biobased molecules with original properties (uses) similar to those of oilbased molecules: *innovation by substitution*;
- Development of molecules or nano-objects with new features to enhance the characteristics of vegetable raw materials: *disruptive innovation*.

Societal controversies

- Safety of biotechnological processes, both industrial accidents and environmental safety of commercial products (REACH).
- Intellectual property, due to *in silico* steps based software tools, broad spectrum of biotech building in very narrow spectrum, marketable for targeted applications.
- The ethics of living with the artificial life, especially in synthetic biology, which may offend certain cultures.

Thank you for your attention

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