Resource Potential of Algae for Sustainable Biodiesel Production in the APEC Economies

David Batten, Peter Campbell and Greg Threlfall
with the assistance of Jeff Skeer (DOE)

Presentation at APEC Workshop on Algal Biofuels
San Francisco, 12 September 2011

Asia-Pacific Economic Cooperation

Project Objectives - Preamble

- **First generation biofuels cannot satisfy the future transport fuel needs of the 21 APEC economies.**
- **They need second generation biofuels, including biodiesel.**
- **Project goal →** to estimate the potential amount and location of algal biomass in the APEC region that can be grown in raceway ponds and used for the sustainable production of biodiesel.
- **Microalgae biomass grown in sunlight holds particular promise because:**
  - It could be a sustainable, relatively low GHG emissions feedstock;
  - It grows rapidly and yields more biodiesel per hectare than plants grown in soil;
  - It contains little or no sulphur or other toxic substances;
  - It is biodegradable and does not destroy natural habitats; and
  - It does not compete directly with food production on arable land.

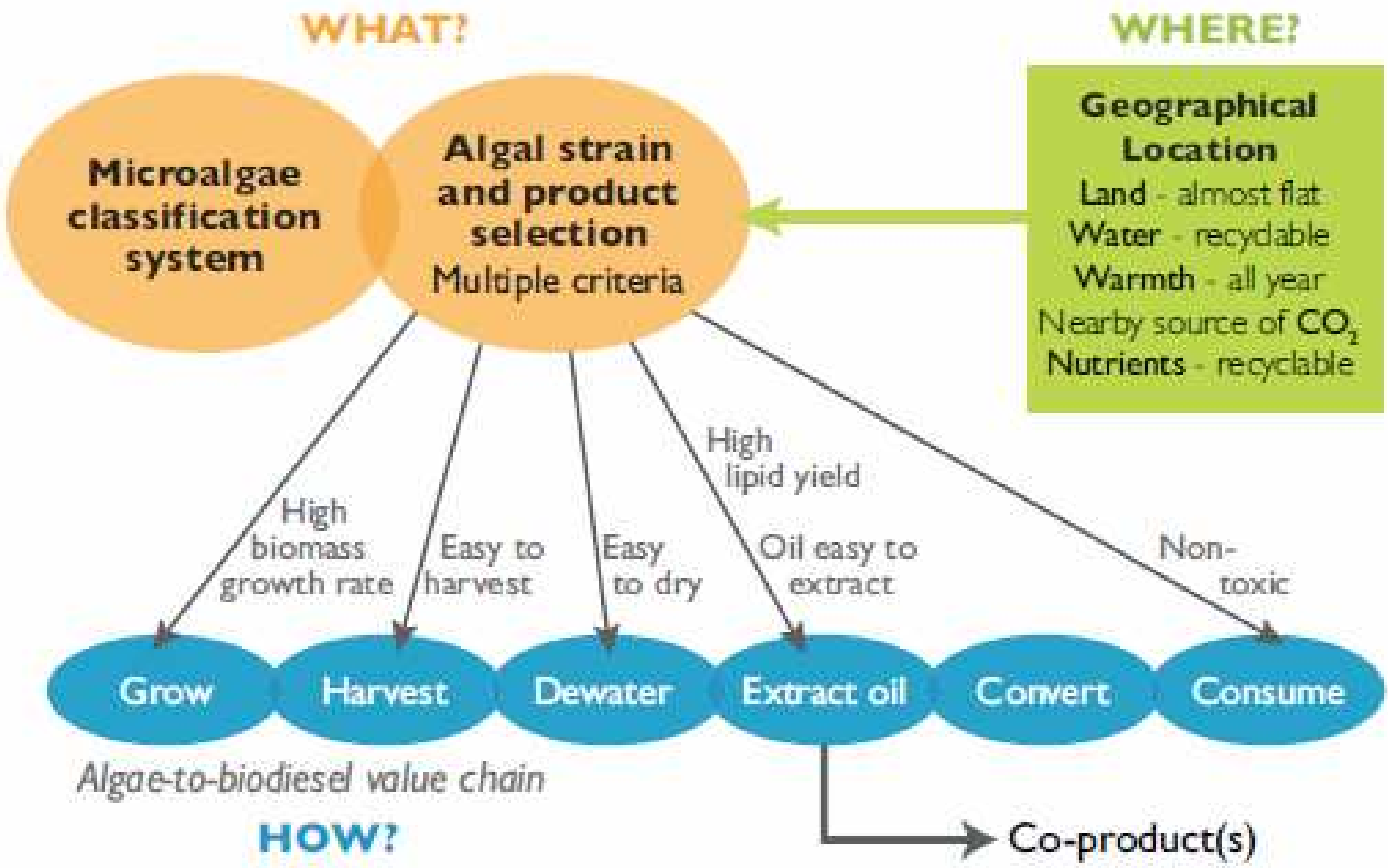
National Research FLAGSHIPS Energy Transformed CSIRO

Potential Usefulness of Project Findings

- Relevant to economic, energy, land and agriculture ministries in developed and developing APEC economies.
- **Typical questions it may help to answer are:**
  - Could *waste streams* – such as human and animal wastes in/near towns and cities – become a sustainable source of algal biodiesel?
  - Could *marginal, coastal land* be used for algal biodiesel production?
  - Should candidate locations be surveyed by governments to gain a fuller understanding of their biodiesel potential?
  - Do limits exist on the *scaling-up* of biodiesel from microalgae owing to competition for key nutrients (C, N and P)?
  - What are the most sustainable ways of displacing fossil diesel for transport?
- **The project should enhance the capacity of officials and experts in developed and developing economies to address these and other related issues.**

National Research FLAGSHIPS Energy Transformed CSIRO

Making Algal Biodiesel



Two Estimation Methods with Dunaliella

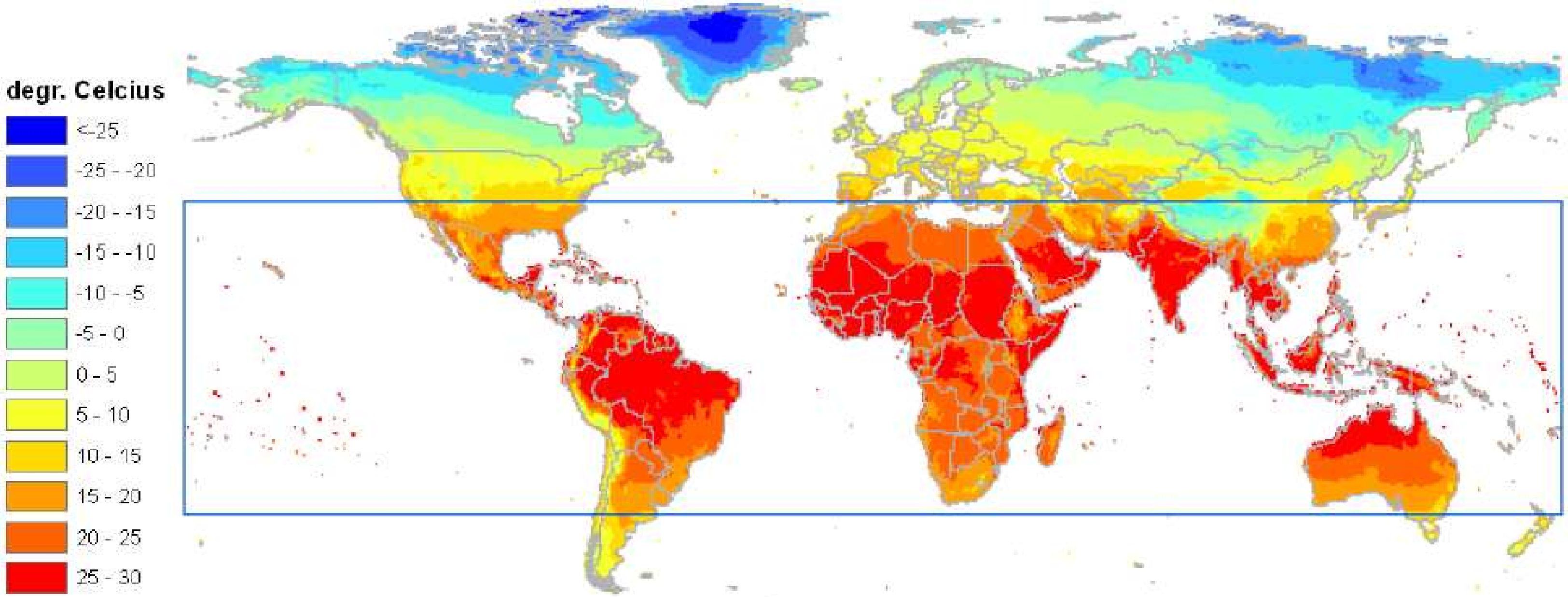
- **Method 1: Leverages human and animal wastes for N and P only (see van Harmelen and Oonk, 2006):**
  - Assumes the limiting factor is N and residual biomass is used for animal feeds – i.e. N and P are not recycled;
  - TNO estimates adjusted down because their analysis assumed all wastewater in each economy was collected and treated;
  - Provides a rough, lower-bound estimate of algal biomass potential in APEC economies over the next 10-15 years.
- **Method 2: As for Method 1, with nutrients (CO_2, N, P and K) coming from wastewater & some nearby power generation:**
  - Assumes the limiting factor is C, with N and P being recycled;
  - Residual biomass may be converted into biogas via anaerobic digestion and biogas combusted to provide power & CO_2;
  - Provides an assessment of extra possibilities in the long-term.

Method 1: Adjusted TNO Approach

- **Step 1:** Given limited data, estimate theoretical possibilities;
- **Step 2**: Introduce constraints to whittle the theoretical resources down to a practical set of achievable possibilities (e.g. Not much land available in Hong Kong or Singapore).
- Such a sequential constraints approach has been used by:
  - **TNO's van Harmelen and Oonk (2006) for global algal biomass;**
  - **CSIRO's Farine et al (2011) and others for terrestrial biomass.**
- Step 2a: **Climate constraint** → temperature and insolation;
- Step 2b: **Water & nutrients (N,P)** → collected wastewater
  - **TNO figures should be adjusted down in each APEC economy because not all wastewater is collected for treatment.**
- Step 2c: **Land available** → a function of altitude & population;
- Step 2d: **CO_2 available** → a function of population densities.

Method 1: Adjusted TNO Approach

Step 2a: Climatic resources:
The TNO approach includes nations that fall within the blue rectangle, i.e. those enjoying annual average temperatures of 15ºC or more.

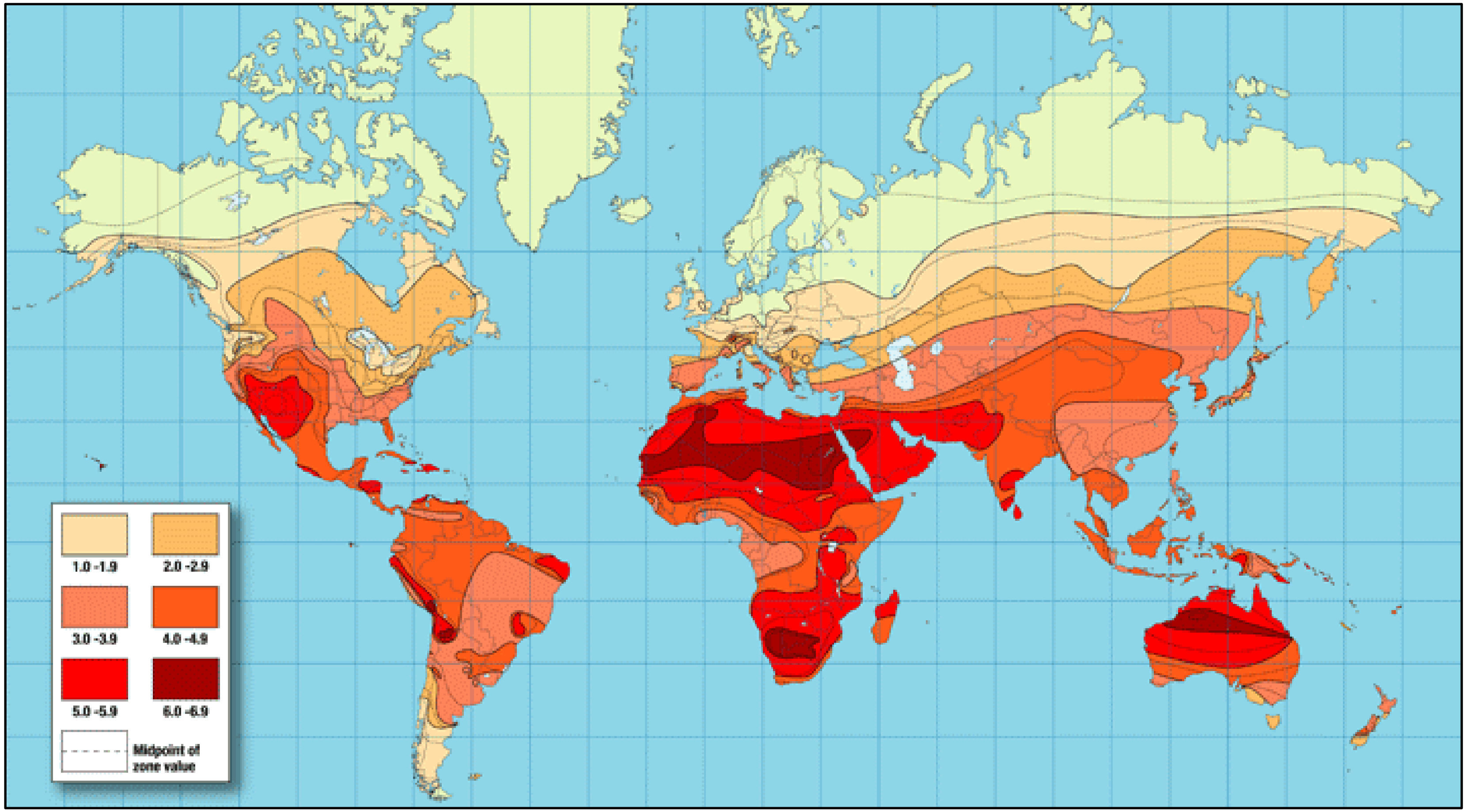


In future, use constraints arising from incident solar radiation, minimum winter and night-time temperatures.

Source: Van Harmelen and Oonk, 2006

National Research FLAGSHIPS Energy Transformed CSIRO

World Daily Solar Radiation Map



Source: OKSolar

Theoretical Algae Resource Production Potential by APEC Economy in 2020

APEC ECONOMIC ZONE	MUNICIPAL WASTE (t)	ANIMAL WASTE (t)	TOTAL WASTE (t)	ALGAE (Mt)	RANK
Australia	217,000	572,400	**789,400**	7.89	
Brunei Darussalam	0	0	**0**	0	
Canada (See Note 1)	**0**	**0**	**0**	**0**	
Chile	7,000	0	**7,000**	0.07	
Peoples Republic of China	**5,257,750**	**5,281,600**	**10,539,350**	105.39	**First**
Hong Kong, China	0	0	**0**	0	
Indonesia	977,500	216,000	**1,193,500**	11.94	
Japan	20,000	11,000	**31,000**	0.31	
Republic of Korea	0	0	**0**	0	
Malaysia	111,000	64,800	**175,800**	1.76	
Mexico	**619,500**	**3,060,700**	**3,680,200**	36.80	**Second**
New Zealand	0	0	**0**	0	
Papua New Guinea	22,000	400	**22,400**	0.22	
Peru	119,750	58,800	**178,550**	1.79	
The Philippines	111,750	99,100	**210,850**	2.11	
Russia (See Note 1)	**0**	**0**	**0**	**0**	
Singapore	0	0	**0**	0	
Chinese Taipei	25,000	30,000	**55,000**	0.55	
Thailand	428,250	299,800	**728,050**	7.28	
United States of America	**848,500**	**1,033,500**	**1,882,000**	18.82	**Third**
Viet Nam	430,500	468,600	**898,600**	8.99	
TOTAL	**9,195,500**	**11,196,200**	**20,391,700**	203.92	

Note 1: Wholly located outside of the 15 degrees C optimal algal growth zone.
Assumes 1 kg of N → 10 kg of algal biomass.

National Research FLAGSHIPS Energy Transformed CSIRO

Method 1: Adjusted TNO Approach

Theoretical Algae Resource Production Potential

Reduction due to Climate Constraints

Location of Waste Nutrient Resources

Reduction due to Wastes Collected

Reduction due to Land Available

Reduction due to CO_2

PARPP

PARPP = Practical Algae Resource Production Potential

National Research FLAGSHIPS Energy Transformed CSIRO

Estimates of Waste Streams "Collected"

APEC ECONOMIC ZONE	Percentage of Human Sewage Collected	Percentage of Cattle in Feedlots	Percentage of Pigs in Medium-Large Piggeries
Australia	87%	5.4%	54%
Brunei Darussalam	40%		
Canada (See Note 1)	74%	20%	40%
Chile	96%		
Peoples Republic of China	46%		
Hong Kong, China	93%		
Indonesia	25%		
Japan	67%		
Republic of Korea	50%		
Malaysia	40%		
Mexico	20%	5.7%	40%
New Zealand	80%		
Papua New Guinea	30%		
Peru	81%		
The Philippines	7%		
Russia (See Note 1)	55%		
Singapore	100%		
Chinese Taipei	85%		
Thailand	40%	0	80%
United States of America	71%	80%	45%
Viet Nam	5%	1%	5%

Note 1: Wholly located outside of the 15ºC optimal algal growth zone

National Research FLAGSHIPS Energy Transformed

CSIRO

Practical Algae Resource Production Potential by APEC Economy in 2020

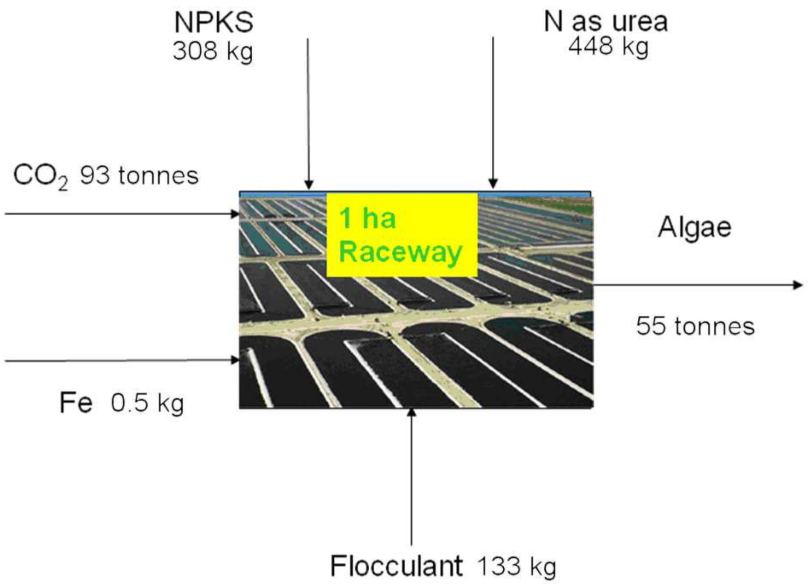
APEC ECONOMIC ZONE`First	MUNICIPAL WASTE (t)	ANIMAL WASTE (t)	TOTAL WASTE (t)	ALGAE (Mt)	BIODIESEL (ML)	AS % OF AUTO DIESEL USAGE	RANK
Australia	32,750	0	**32,750**	**0.33**	**110**	**1.0%**	
Brunei Darussalam	0	1,750	**1,750**	**0.02**	**6**	**2.9%**	
Canada (See Note 1)	0	0	0	**0**	**0**	**0**	
Chile	0	3,000	**3,000**	**0.03**	**10**	**0.2%**	
Peoples Republic of China	**989,500**	**1,760,000**	**2,749,500**	**27.5**	**9,165**	**9.5%**	**First**
Hong Kong, China	0	0	**0**	**0**	**0**	**0**	
Indonesia	**610,250**	**99,500**	**709,750**	**7.1**	**2,366**	**15.4%**	**Third**
Japan	0	14,000	**14,000**	**0.14**	**47**	**0.1%**	
Republic of Korea	0	4,800	**4,800**	**0.05**	**17**	**0.1%**	
Malaysia	76,250	45,000	**121,250**	**1.21**	**404**	**5.4%**	
Mexico	108,250	294,500	**402,750**	**4.03**	**1,343**	**6.7%**	
New Zealand	0	7,500	**7,500**	**0.07**	**25**	**0.9%**	
Papua New Guinea	0	0	**0**	**0**	**0**	**0**	
Peru	5,500	1,500	**7,000**	**0.07**	**23**	**0.6%**	
The Philippines	71,750	105,000	**176,750**	**1.77**	**589**	**4.0%**	
Russia (See Note 1)	0	0	0	**0**	**0**	**0**	
Singapore	0	0	**0**	**0**	**0**	**0**	
Chinese Taipei	0	0	**0**	**0**	**0**	**0**	
Thailand	334,000	245,000	**579,000**	**5.79**	**1,930**	**5.3%**	
United States of America	**542,250**	**234,400**	**776,650**	**7.76**	**2,589**	**1.3%**	**Second**
Viet Nam	93,750	135,000	**228,750**	**2.29**	**762**	**3.3%**	
TOTAL	**2,864,250**	**3,190,950**	**6,055,200**	**51.77**	**20,184**		

Note 1: Wholly located outside of the 15 degrees C optimal algal growth zone

National Research FLAGSHIPS Energy Transformed

CSIRO

Method 2: Sustainable Inputs Approach



Source: Campbell, Beer and Batten, 2009

- Key nutrients (CO_2, N, P and K) from wastes and on-site power;
- Limiting factor will be amount of carbon available;
- Facilities have water available to produce algal biomass in ponds;
- Oil extracted from biomass and processed into biodiesel;
- Nutrients recycled;
- Residual biomass converted into biogas via anaerobic digestion;
- Biogas combusted to provide electric power & CO_2 on-site;
- Pathway based on Oswald and Golueke (1960) and many others.

Practical Algae Resource Production Potential in APEC: Near and Long Term

APEC ECONOMIC ZONE	METHOD 1: unadjusted ALGAE (Mt)	METHOD 2: ºC adjusted ALGAE (Mt)	METHOD 2: ºC unadjusted ALGAE (Mt)	BIODIESEL (ML) Near	BIODIESEL (ML) Long	AS % OF AUTO DIESEL USAGE Near	AS % OF AUTO DIESEL USAGE Long
Australia	0.33	3.28	3.28	110	1,066	1.0%	9.6%
Brunei Darussalam	0.02	0.05	0.05	6	15	2.9%	7.4%
Canada (See Note 1)	0	0	4.77	0	1,550	0	8.0%
Chile	0.03	0.75	1.50	10	488	0.2%	10.0%
Peoples Republic of China	**First** 27.5	**Second** 36.7	**Second** 73.4	9,165	23,855	9.5%	24.8%
Hong Kong, China	0	0.57	0.57	0	185	0	12.4%
Indonesia	**Third** 7.1	**Third** 5.73	5.73	1,862	2,366	15.4%	19.5%
Japan	0.14	3.57	**Third** 7.14	47	2,320	0.1%	6.2%
Republic of Korea	0.05	2.19	2.19	17	712	0.1%	3.3%
Malaysia	1.21	1.12	1.12	364	404	5.4%	5.9%
Mexico	4.03	4.02	4.02	1,340	1,343	6.7%	6.7%
New Zealand	0.07	0.04	0.39	25	127	0.9%	4.5%
Papua New Guinea	0	0.21	0.21	0	68	0	70%
Peru	0.07	2.23	2.23	23	725	0.6%	20.3%
The Philippines	1.77	0.92	0.92	299	589	4.0%	7.9%
Russia (See Note 1)	0	0	6.70	0	2,178	0	11.7%
Singapore	0	0.51	0.51	0	166	0	7.8%
Chinese Taipei	0	1.75	1.75	0	569	0	1.0%
Thailand	5.79	2.71	2.71	881	1,930	5.3%	11.7%
United States of America	**Second** 7.76	**First** 45.8	**First** 91.5	2,589	29,738	1.3%	14.5%
Viet Nam	2.29	0.58	0.58	189	762	3.3%	13.2%
TOTAL	51.77	112.73	211.27				

Note 1: Wholly located outside of the 15 degrees C optimal algal growth zone

National Research FLAGSHIPS Energy Transformed CSIRO

Methodological Strengths/ Weaknesses

- Method 1: Although crudely constructed, the TNO adjusted estimates have considered all the key constraints:
  → our best near-term estimates for APEC economies.
- Method 2: With a total of 211 Mt of algal biomass, C-limited estimates exceed Method 1's theoretical maximum (204 Mt) primarily because available land has not been assessed:
  → unreliable without adjustments for land availability and availability of other resources, including nutrient sources.
- Large areas of coastal land are scarce and costly in most APEC economies, so availability and cost of land will need more detailed analysis in a future APEC study
- Combining several approaches is worth considering:

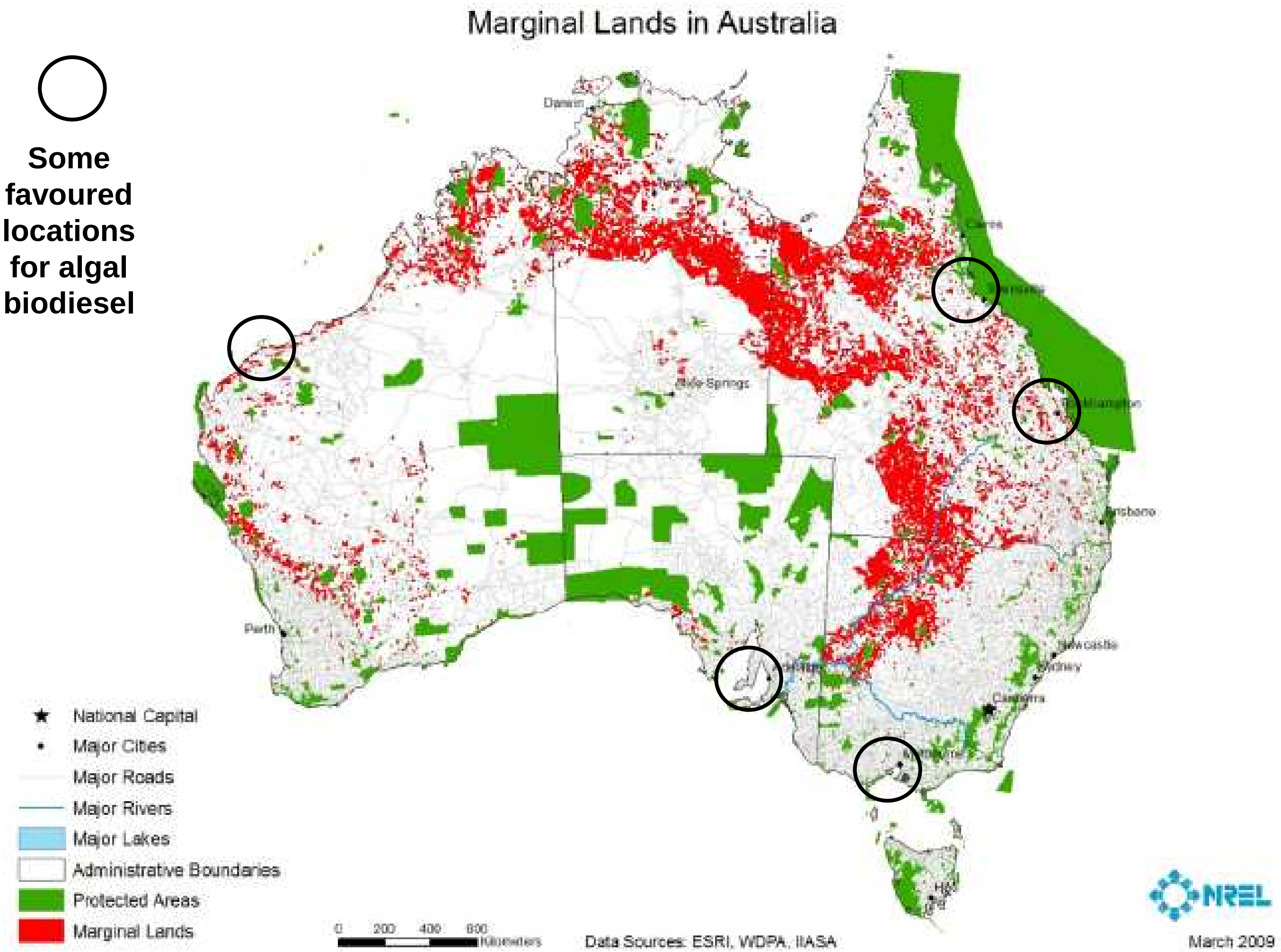
  (1) Estimates of coastal land available in the APEC study by Milbrandt and Overend (2009) and others with

  (2) GIS-based models for selecting potential sites.

National Research FLAGSHIPS Energy Transformed CSIRO

Future: Marginal Coastal Land + Nutrients

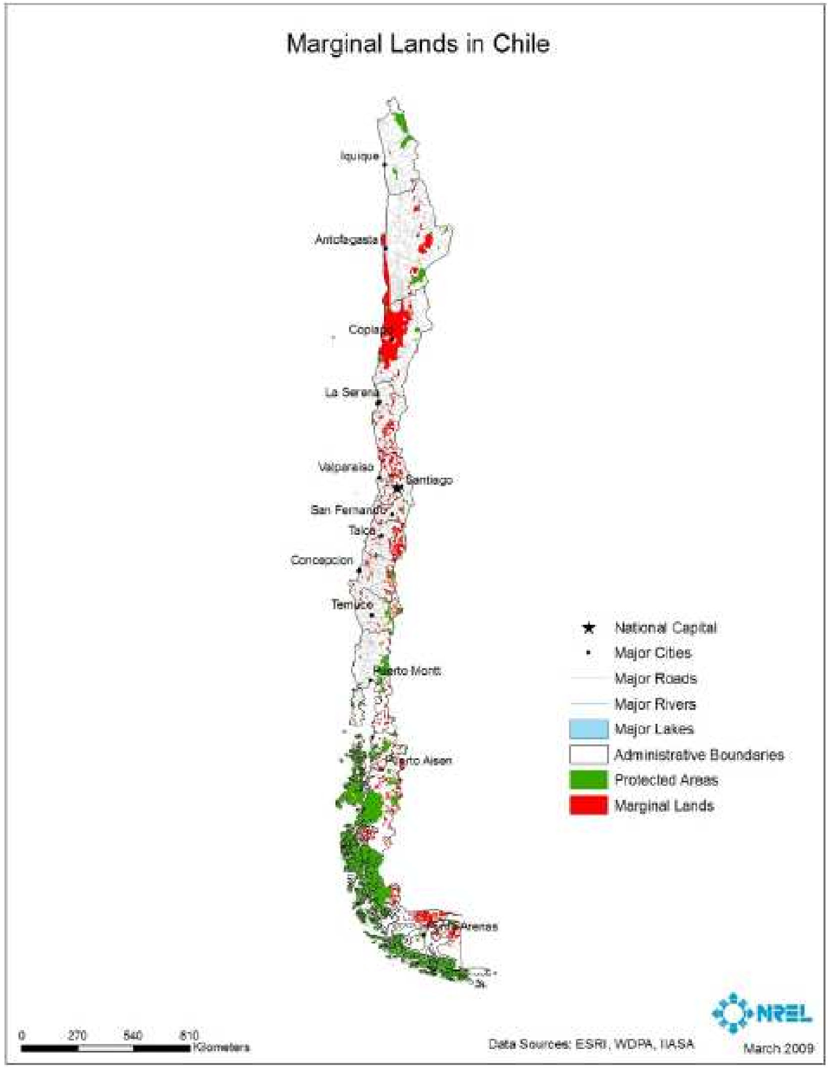
Some favoured locations for algal biodiesel



Source: Milbrandt and Overend, 2009

National Research FLAGSHIPS Energy Transformed
CSIRO

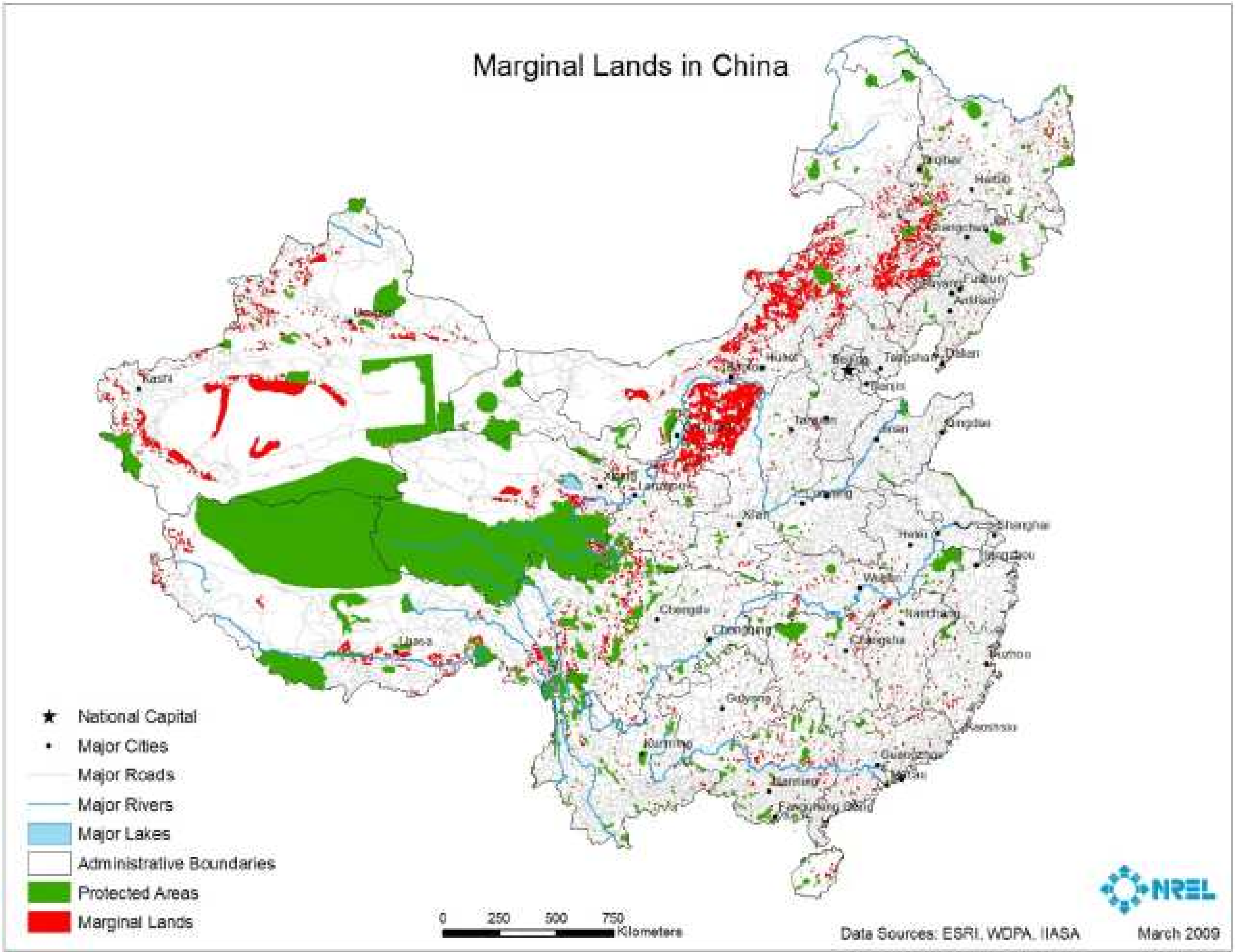
Future: Marginal Coastal Land + Nutrients



Source: Milbrandt and Overend, 2009

National Research FLAGSHIPS Energy Transformed CSIRO

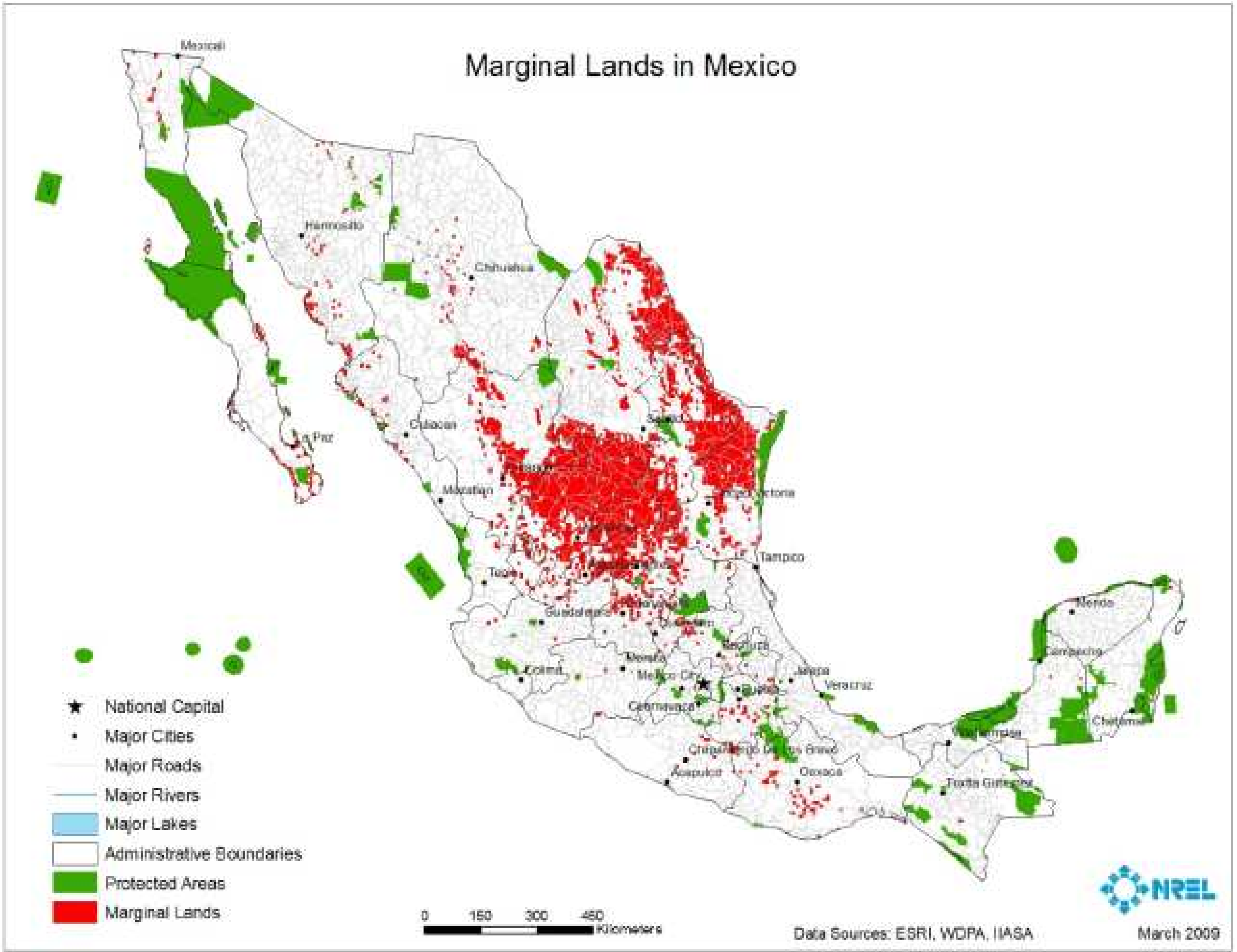
Future: Marginal Coastal Land + Nutrients



Source: Milbrandt and Overend, 2009

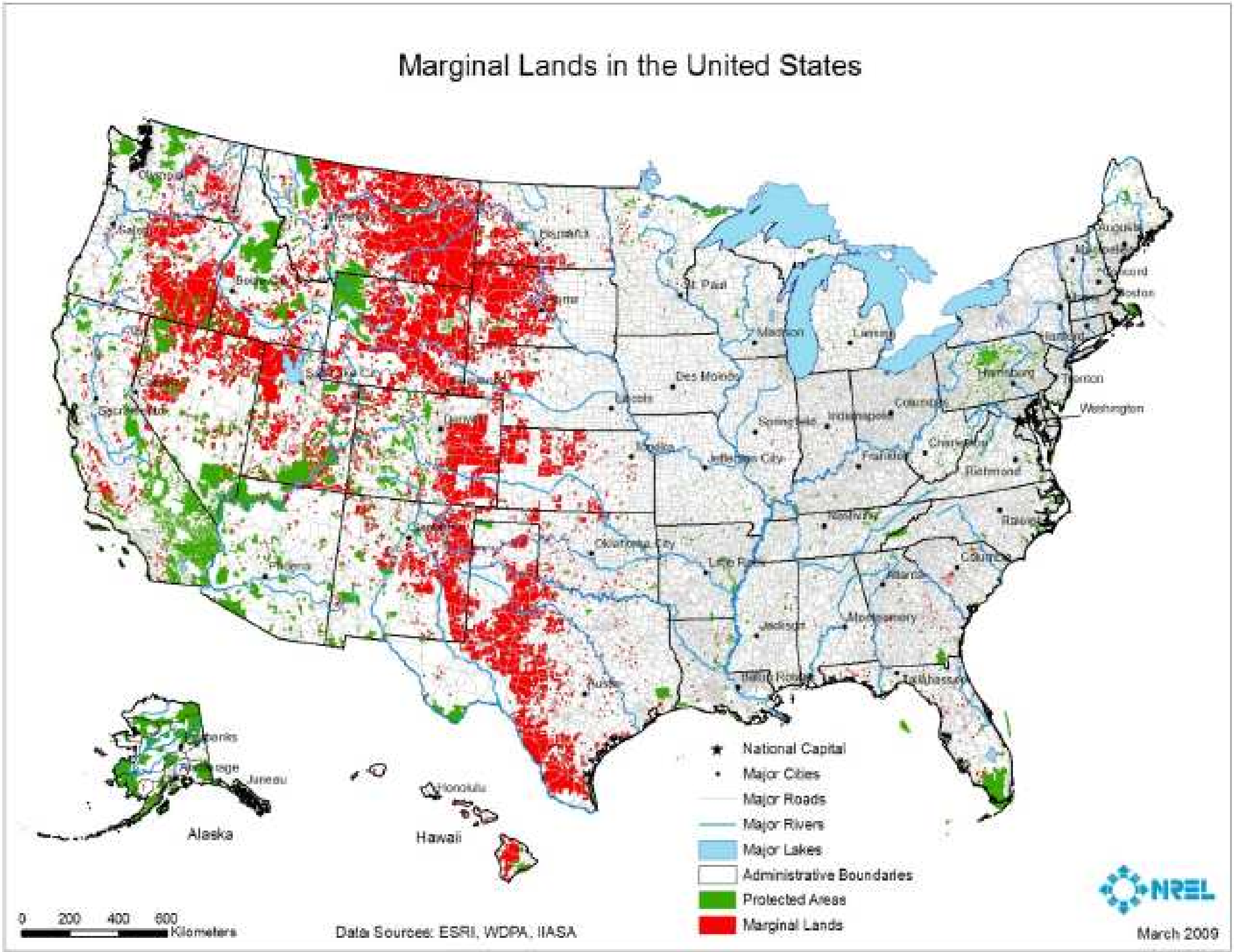
National Research FLAGSHIPS
Energy Transformed
CSIRO

Future: Marginal Coastal Land + Nutrients



Source: Milbrandt and Overend, 2009

Future: Marginal Coastal Land + Nutrients



Source: Milbrandt and Overend, 2009

Future: Marginal Coastal Land + Nutrients

APEC ECONOMIC ZONE	Land area (hectares)	Marginal Land (% of land area)	Marginal Coastal Land (ha)
Australia	**769 million**	**13.50%**	**t.b.c.**
Brunei Darussalam	0.6 million	1.40%	t.b.c.
Canada	983 million	3.80%	t.b.c.
Chile	**72 million**	**13.00%**	**t.b.c.**
People's Republic of China	940 million	5.40%	t.b.c.
Indonesia	185 million	2.00%	t.b.c.
Japan	37 million	1.30%	t.b.c.
Korea	9.5 million	1.70%	t.b.c.
Malaysia	33 million	1.00%	t.b.c.
Mexico	**195 million**	**13.00%**	**t.b.c.**
New Zealand	27 million	6.50%	t.b.c.
Papua New Guinea	46 million	1.60%	t.b.c.
Peru	130 million	4.40%	t.b.c.
Philippines	28 million	2.30%	t.b.c.
Russia	1,690 million	2.20%	t.b.c.
Chinese Taipei	3.6 million	2.20%	t.b.c.
Thailand	52 million	3.30%	t.b.c.
United States of America	**943 million**	**13.00%**	**t.b.c.**
Viet Nam	32 million	6.50%	t.b.c.

(Milbrandt and Overend, 2009)

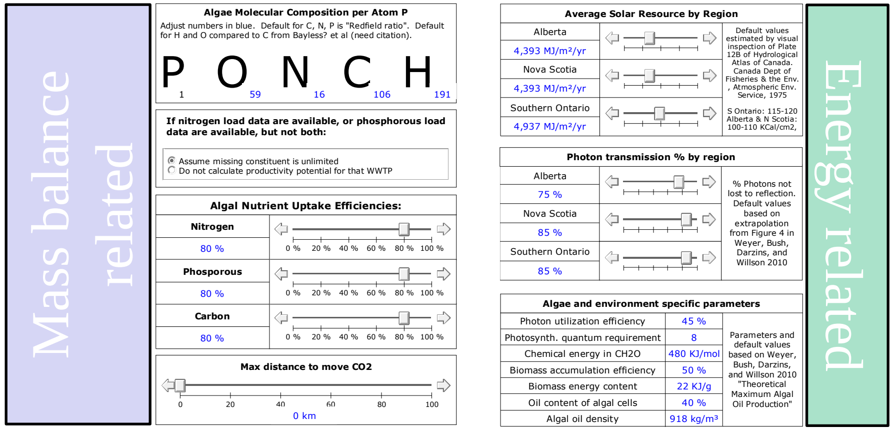
National Research FLAGSHIPS Energy Transformed CSIRO

Future: GIS-Based Site Selection Models

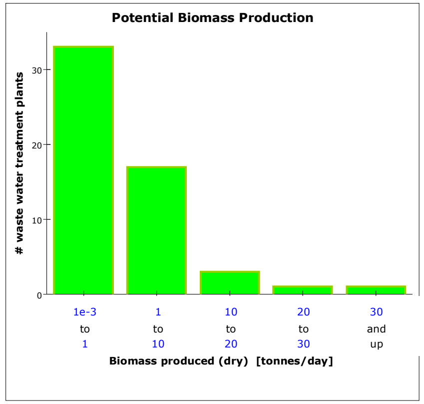
Data on wastewater treatment plants and sources of CO_2

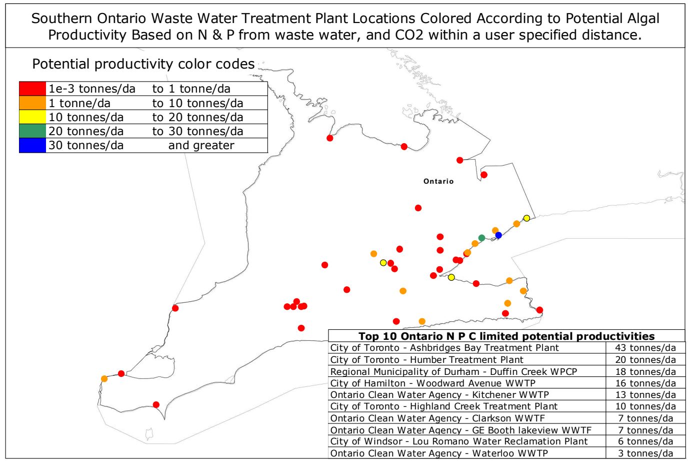
Nutrient availability & locations for wastewater treatment plants & CO_2 sources in the USA and Canada. Australia being added now.

User defined model parameters



Visualization



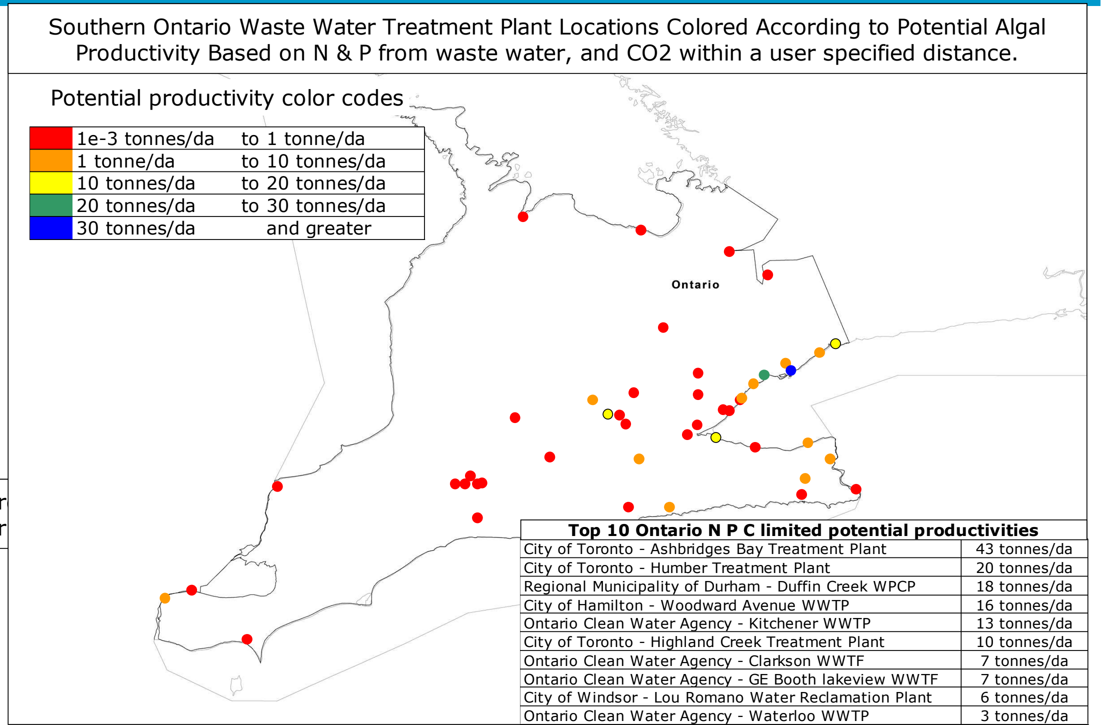


(Source: Sandia National Laboratories)

Future: GIS-Based Site Selection Models

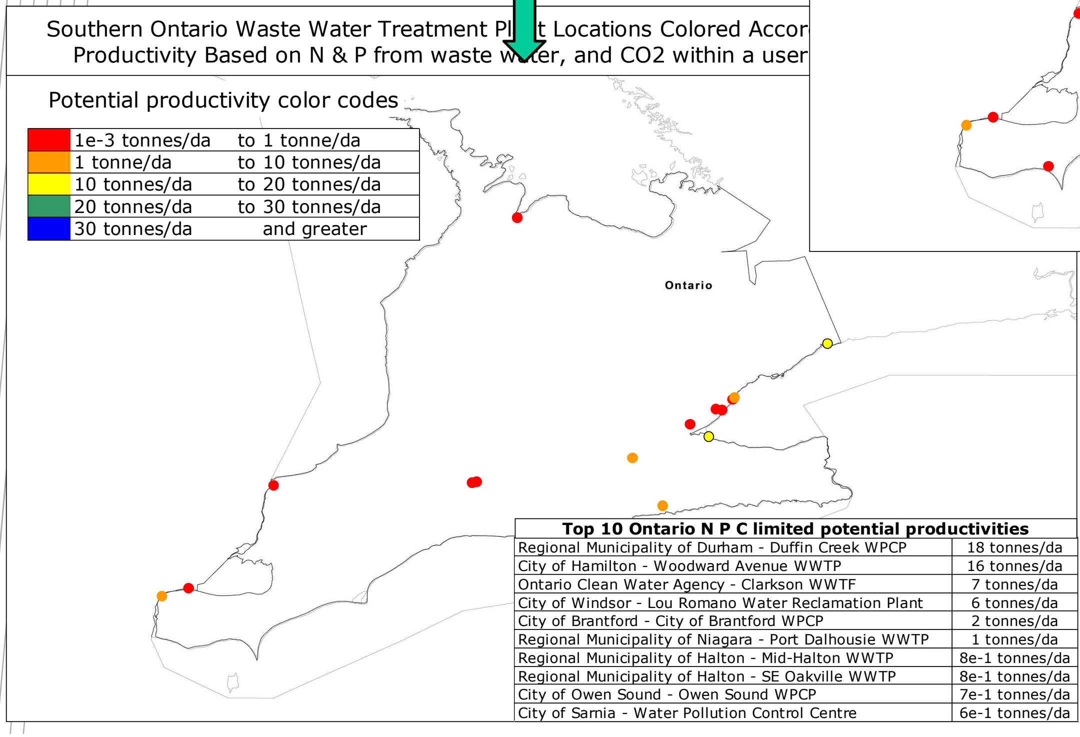
Southern Ontario Potential Algal productivity

Using CO_2 sources within 85 km:



Top 10 Ontario N P C limited potential productivities	
City of Toronto - Ashbridges Bay Treatment Plant	43 tonnes/da
City of Toronto - Humber Treatment Plant	20 tonnes/da
Regional Municipality of Durham - Duffin Creek WPCP	18 tonnes/da
City of Hamilton - Woodward Avenue WWTP	16 tonnes/da
Ontario Clean Water Agency - Kitchener WWTP	13 tonnes/da
City of Toronto - Highland Creek Treatment Plant	10 tonnes/da
Ontario Clean Water Agency - Clarkson WWTF	7 tonnes/da
Ontario Clean Water Agency - GE Booth lakeview WWTF	7 tonnes/da
City of Windsor - Lou Romano Water Reclamation Plant	6 tonnes/da
Ontario Clean Water Agency - Waterloo WWTP	3 tonnes/da

Using CO_2 sources within 10 km:



Top 10 Ontario N P C limited potential productivities	
Regional Municipality of Durham - Duffin Creek WPCP	18 tonnes/da
City of Hamilton - Woodward Avenue WWTP	16 tonnes/da
Ontario Clean Water Agency - Clarkson WWTF	7 tonnes/da
City of Windsor - Lou Romano Water Reclamation Plant	6 tonnes/da
City of Brantford - City of Brantford WPCP	2 tonnes/da
Regional Municipality of Niagara - Port Dalhousie WWTP	1 tonnes/da
Regional Municipality of Halton - Mid-Halton WWTP	8e-1 tonnes/da
Regional Municipality of Halton - SE Oakville WWTP	8e-1 tonnes/da
City of Owen Sound - Owen Sound WPCP	7e-1 tonnes/da
City of Sarnia - Water Pollution Control Centre	6e-1 tonnes/da

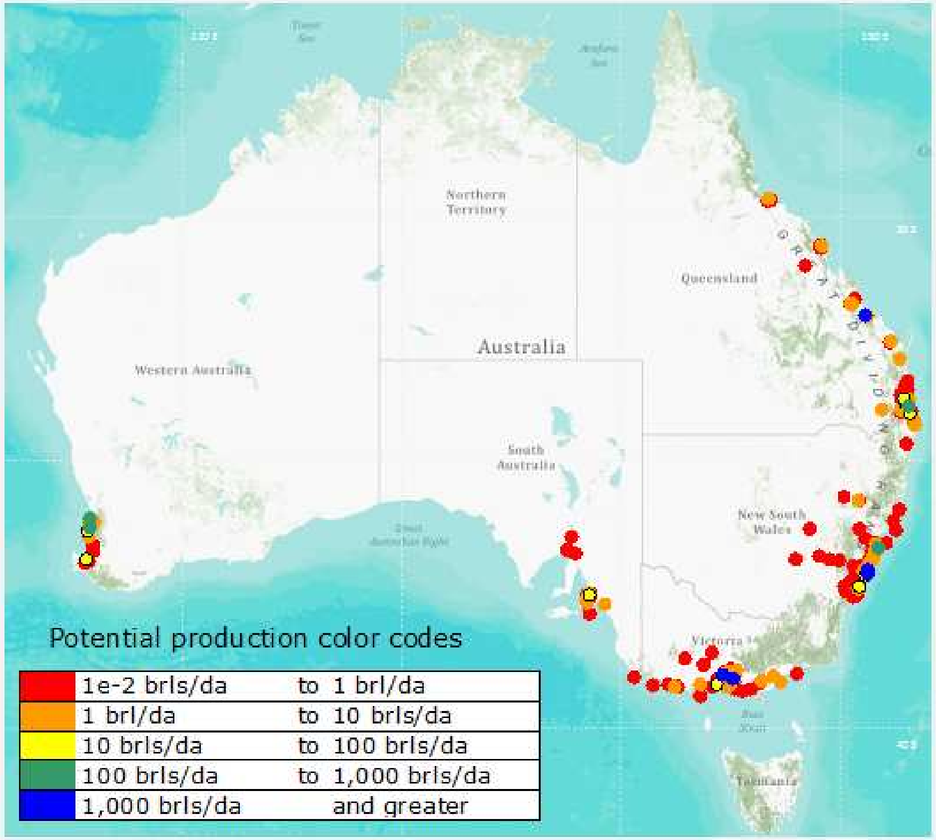
The best sites change as distance to the CO_2 constraint is relaxed (Only 3 of top 10 sites for 10 km are in top 10 for 85 km).

(Source: Sandia National Laboratories)

National Research FLAGSHIPS Energy Transformed
CSIRO

Future: GIS-Based Site Selection Models

Australia nitrogen and phosphorous (N&P) production locations colored according to potential algal biocrude production for distance from N&P location to CO2 location of no more than **200 km**



Top 30 potential biocrude production sites

Malabar Sewage Treatment Plant	131,156 l/da
Eastern Treatment Plant	129,956 l/da
North Head Sewage Treatment Plant	109,029 l/da
Western Treatment Plant	46,169 l/da
Bondi Sewage Treatment Plant	40,908 l/da
Rio Tinto Aluminium Yarwun	20,750 l/da
Burwood Beach Wastewater Treatment Works	13,802 l/da
Luggage Point WWTP	13,673 l/da
Beenyup Wastewater Treatment Plant	13,185 l/da
Woodman Point WWTP	12,486 l/da
Bolivar Wastewater Treatment Plant	9,149 l/da
Cronulla Sewage Treatment Plant	9,113 l/da
Bunbury Wastewater Treatment Plant	6,743 l/da
Black Rock Water Reclamation Plant	6,717 l/da
Point Peron Wastewater Treatment Plant	6,535 l/da
Murrumba Downs Sewage Treatment Plant	6,366 l/da
Water Pollution Control Centre	5,840 l/da
South Caboolture STP WRP	5,714 l/da
Wollongong Sewage Treatment System	5,648 l/da
Subiaco Wastewater Treatment Plant	5,253 l/da
Oxley Creek Wastewater Treatment Plant	5,203 l/da
Gibson Island WWTP	4,655 l/da
Glenelg Wastewater Treatment Plant	3,673 l/da
Cargill Meat Processors Tamworth	3,596 l/da
Murray Bridge Wastewater Treatment Plant	3,442 l/da
Queensland Alumina Ltd	3,087 l/da
Brendale Sewage Treatment Plant	3,060 l/da
Kincumber Sewage Treatment Plant	3,057 l/da
Bribie Island Sewage Treatment Plant	3,028 l/da
Warriewood Sewage Treatment Plant	2,750 l/da

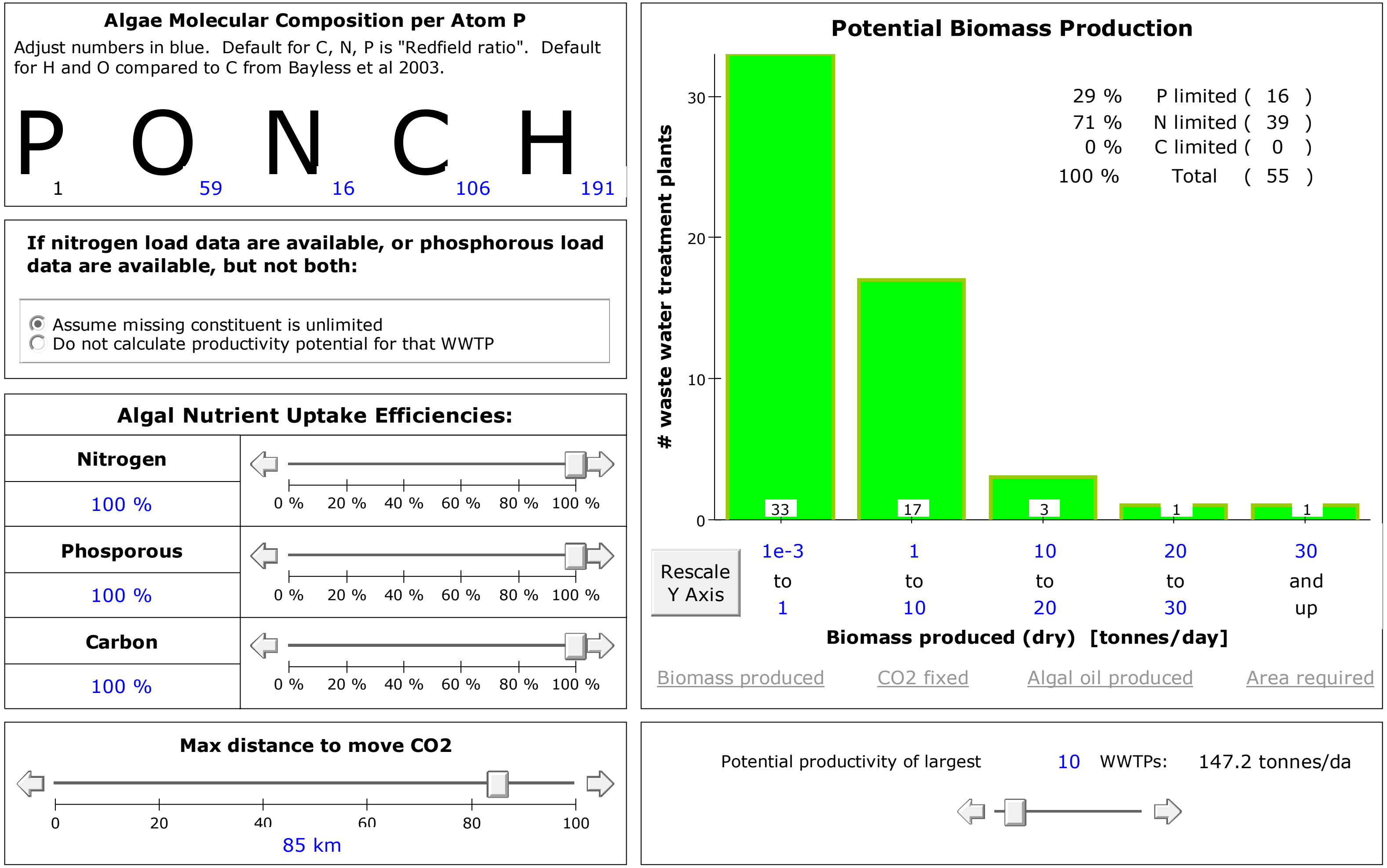
All N&P sources : 711,943 l/da

Biocrude Histogram View   or, other map views: Biomass produced   CO2 fixed   Algal oil produced   Area required

(Source: Sandia National Laboratories)

National Research FLAGSHIPS Energy Transformed CSIRO

Future: GIS-Based Site Selection Models



(Source: Sandia National Laboratories)

Some Preliminary Conclusions

- For several compelling reasons, resources most suited to near-term application of microalgae cultures for biodiesel production are **human, animal** and some **industrial wastes.**
- Eventually, the **USA** and **China** may be the APEC economies with the largest potential for growing algal biomass in sunlight for energy purposes using waste streams.
- Interestingly, **China** grows *Chlorella* in the dark, mostly for use as a nutritional supplement.
- Other APEC economies with significant potential are **Indonesia, Mexico** and **Thailand**.
- **Australia** and **Chile** have limited potential unless large tracts of their marginal land can be exploited profitably and sustainably.
- **Even if optimistic, APEC economies are unlikely to replace more than 10–15% of their diesel use with algal biodiesel.**

www.csiro.au

Energy Transformed Flagship

David Batten
Low-Cost Algal Fuels
Transport Technologies and Sustainable Fuels

Phone: +61 3 9239 4420
Email: david.batten@csiro.au

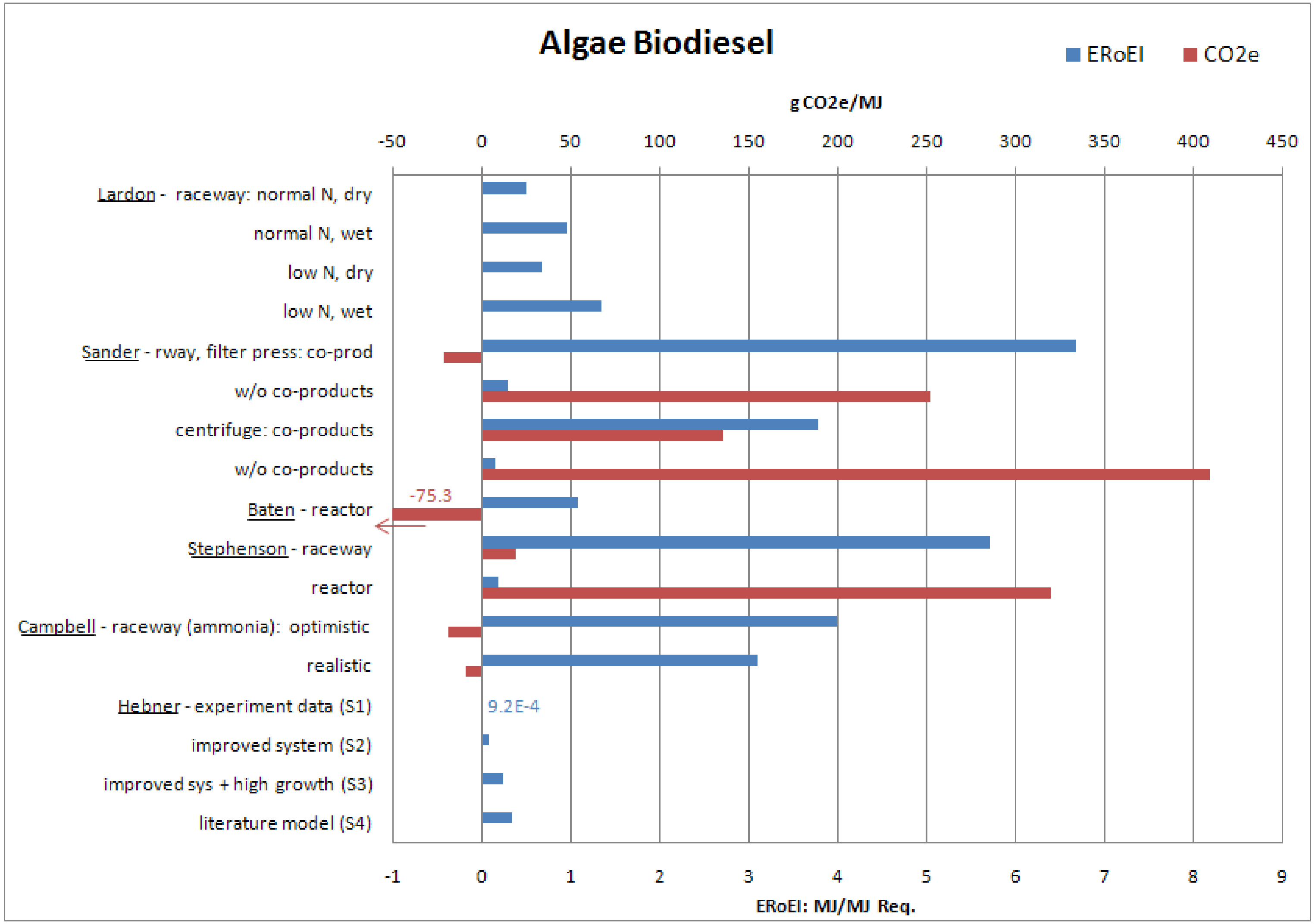
Thank you

Contact Us
Phone: 1300 363 400 **or** +61 3 9545 2176
Email: Enquiries@csiro.au **Web:** www.csiro.au

National Research FLAGSHIPS Energy Transformed

CSIRO

How Sustainable is this Pathway?



Source: Rye, Beer and Batten (2011)